VOLUME AND RATE OF STREAM DISCHARGE FROM AN ALPINE SNOWPACK

BY T. CARROLL AND N. CAINE

VOLUME AND RATE OF STREAM DISCHARGE FROM AN ALPINE SNOWPACK.

A final report to the Eisenhower Consortium for Western Environmental Forestry Research.

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Rocky Mountain Forest and Range Experimental Station, U.S.D.A., Fort Collins, Colorado.

T. Carroll
N. Caine
Institute of Arctic and Alpine Research
University of Colorado
Boulder, Colorado

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CHAPTER I

INTRODUCTION

This is the final report of a two year hydrologic study of an alpine catchment in the Colorado Front Range. It summarizes observations and data collected in the 1972-1974 period and interprets them in terms of the events and processes involved in the snowmelt control of streamflow from the alpine area. The work has been conducted under research agreement No. 16-292-CA between the U.S. Department of Agriculture, Rocky Mountain Forest and Range Experimental Station and the University of Colorado, Institute of Arctic and Alpine Research.

Objectives

The study defines the spatial and temporal patterns of snow accumulation in and water yield from a stream catchment above tree line in the southern Rockies. Most emphasis has been placed on the hydrologic events leading to and immediately following the period of peak snowmelt and streamflow in late spring and early summer. Three objectives, defined early in the study will be considered in turn here. These are:

1. The measurement of the areal extent, depth and density of the winter snow cover, especially at the time of maximum accumulation.
2. The establishment of ablation rates on a variety of snow surfaces in the basin to give estimates of the liquid water input which eventually leads to streamflow.
3. The measurement of the stream discharge from the catchment; that is, its available water resource.

This Report

With some additional observations, the realisation of these three objectives would allow computation of a water budget for the alpine area. The report is, therefore, set out as a set of basic budget terms:

$$Q = P - Et - \Delta S \qquad (1)$$

where Q = stream discharge;

P = one or more precipitation terms;

Et = sum of evaporation, sublimation and transpiration losses and gains;

ΔS = sum of storage changes within the basin (in the snowpack, soil and ground water and lakes).

In evaluating equation (1), all terms must be stated in the same units, usually as depths of water (cm) or water equivalent or as volumes (m^3). In this study, it has not been possible to define a water budget for the basin on a shorter time scale than a week although some of the terms in equation (1), particularly Q, can easily be treated on a daily, or shorter, frequency.

In this report, equation (1) is treated in two parts. The first concerns the input of water to the stream system and involves both summer rainfall and the storage changes within the basin that occur on snowmelt. The second comprises the basin outflow, either as stream discharge or evapotranspiration loss. A final chapter draws this together in estimating seasonal water budgets for the basin on a weekly time scale.

The Field Area

All observations were made in the Green Lakes Valley (40° 3' N.; 105° 37' W) in the Indian Peaks sector of the Colorado Front Range (Figure 1). This is a glaciated valley cut in granitic and gneissic bedrock which drains east from the Continental Divide to Lake Albion, $3\frac{1}{2}$ km away. The valley has a simple, sub-rectangular shape and a similarly simple drainage pattern consisting of a main stem which joins a linear cascade of four lakes.

The upper 192 ha of the basin (drained through the outlet of Green Lake 4) have been studied separately and will be referred to here as the 'Upper Basin'. This part of the catchment is higher and more obviously alpine than the lower part and so has been stressed in the study. There is also a difference in the nature of the lakes in the upper and lower parts of the catchment: those in the lower part are impounded and their levels controlled.

(Green Lake 2 was drawn down in Fall, 1972 which complicates use of the discharge record at Lake Albion during the following Spring.) The characteristics of the two catchments are summarized in Table 1.

The long-term climate of the Green Lakes Valley can be estimated from the records of the D-1 station at 3750 m elevation on Niwot Ridge immediately to the north of the valley. These records have been analysed by Barry (1972; 1973). They show mean temperatures of -13.2^{o} C in January and 8.3^{o} C in July with an annual mean of -3.8^{o} C. The mean annual precipitation is 102.08 cm (based on only 5 yrs of record) with a slight maximum in winter and a minimum in the fall. An important characteristic of the D-1 site is its windiness (mean annual wind speed is 10.3 m sec^{-1}) which is important in drifting the winter snowfall and concentrating the water stored as snow in drift situations.

The Observational Record

Observations in the Green Lakes Valley were concentrated in the spring, summer and fall seasons of 1973 and 1974, although data from the latter part of the 1974 runoff season are not included here. The occasions of survey and the period of record are summarized in Table 2, while the data are included as appendices to this report.

Table 2 summarizes only the main observations made routinely in the Green Lakes Basin. Other observations and estimates of environmental characteristics were made at the same time in the valley and additional relevant information is also available from the D-1 weather station records. Where necessary, these are all used in this report.

Computer Modeling

Appendix 4 gives a detailed description of the computer model developed by Williams (1974) and uses the 1973 Green Lakes data to test the model.

TABLE 1

GREEN LAKES VALLEY

	Elevation (Outlet)	Relief	Order[1)]	Shape[2)]	Channel Length
Entire Basin	3350 m	734 m	1(3)	2.23	5.45 km
Upper Basin	3354 m	536 m	1(3)	2.23	4.05 km

	Drainage Density	Area	Lake Area	Lake Volume	Vegetation Area
Entire Basin	1.80 km^{-1}	302 ha	22.62 ha	1.51×10^6 m^3	29.14 ha
Upper Basin	2.12 km^{-1}	191 ha	8.38 ha	0.34×10^6 m^3	24.80 ha

	Unvegetated Area (Talus & Bedrock)	Bog & Wetland
Entire Basin	239.32 ha	10.86 ha
Upper Basin	155.81 ha	5.26 ha

1) Order as defined by the Horton-Strahler convention (Leopold, Wolman & Miller 1964, Chap. 5).

2) Shape is the length - width ratio meanured from the outlet.

TABLE 2

THE OBSERVATIONAL RECORD

	1973	1974
Snow Accumulation (Peak)	May 18	May 17
Ablation Record (Weekly Interval)	June 19 - Aug. 20	June 17 - Sept. 9
Snow Density	5 occasions	3 occasions
Summer Precipitation (Recording Gauge)	May 6 - Oct. 31	May 17 - Sept. 30
Stream Discharge (2 Stage Recorders)	June 15 - Oct. 31	June 19 - Sept. 30
Discharge Measurement (For Stage Calibration)	16 occasions for Upper Basin 40 occasions for entire Basin	1973 only

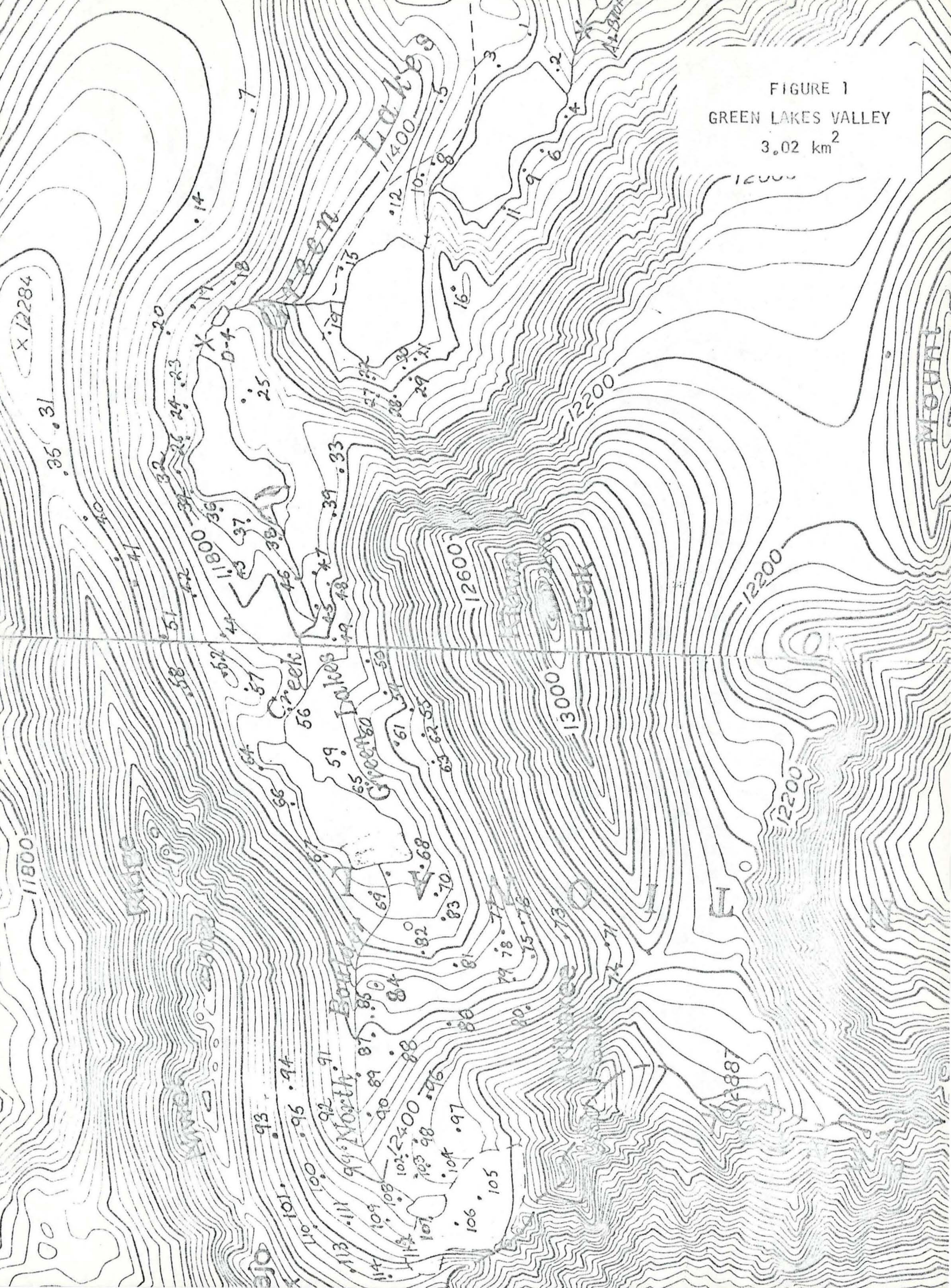


FIGURE 1
GREEN LAKES VALLEY
3.02 km^2

CHAPTER II

INPUT TO SEASONAL WATER BUDGET

SNOW WATER EQUIVALENT AT PEAK SNOW ACCUMULATION

In order to derive the various components of a water balance, it is necessary first to have some index of precipitation. This can be established in two ways. One, a continuous record of precipitation can be made by recording rain gauges (Rodda, 1967). However, in areas where much of the precipitation falls as snow, rain gauges seriously underestimate the total precipitation because of wind effects (Hamon, 1972; Garstka, et al., 1958). The second and more common method of estimating solid precipitation in mountainous areas is the snow survey (U.S. Army, 1956; Garstka, et al., 1958; Golding, 1972b), as used in this study. This yields estimates of the water stored in the watershed on the survey date. The snow survey, by itself, indicates the accumulated net balance of the snowfall, snowmelt, evaporation and possible rainfall in the period before the survey or between two surveys.

Snow Course Description

A snow course of 114 points was used in the Green Lakes Valley to estimate snow water equivalent and measure ablation in the basin (Fig. 1). The basin was stratified on elevation, slope, aspect, and estimated snow depth. Consequently, any point or homogeneous area in the basin can be described by a four-element term which describes the nature of each of the four descriptive basin categories. The four categories are:

(1) Elevation - four elevational zones of roughly equal area (Table 3)

1 - 3353 to 3566 m

2 - 3566 to 3658 m

3 - 3658 to 3780 m

4 - 3780 to 4087 m

TABLE 3

ELEVATION STRATIFICATION

Elevation Number	Elevation Range (m)	Area (ha) (% of total area)	Mean elevation of snow-course	Number of snowcourse points with-in range
1	3353-3566	74.7 (24.7)	3473	26
2	3566-3658	66.5 (22.0)	3609	36
3	3658-3780	80.8 (26.7)	3712	30
4	3780-4087	80.5 (26.6)	3828	22
		302.5		114 total

(2) Slope - three slope angle classes

steep (over 20°)

medium (7.5° - 20°)

flat (less than 7.5°)

(3) Aspect - four aspect classes

North

South

East

Flat (same as the flat area of the slope category)

(Since the basin runs West to East, West facing slopes are practically absent and do not appear in the classification.)

(4) Depth - a three way classification according to general snow accumulation characteristics; deep, medium, and light accumulation areas. This classification was based on available air photographs; areas not snow covered on Sept. 24, 1957, (a high snow year) are considered to be light accumulation areas. Those areas snow covered on Sept. 6, 1956, (a light snow year) are considered to be heavy accumulation areas; the remaining area is classified as a medium accumulation area.

This stratification gives a possible 108 "homogeneous" areas (flat areas are duplicated in the slope and aspect categories). Since it has been suggested that elevation controls accumulation more strongly than either aspect or slope (U.S. Army, 1956; Golding, 1968a, 1968b, 1972; Meiman, 1968), snow accumulation has been examined in matrices of: elevation by slope, elevation by aspect, and elevation by depth. These three matrices give the 36 homogeneous areas which are used in this study. The 108 potential areas have been reduced to 36 areas which respond similarly (Tables 4 and 5). Because basin accumulation and ablation data are examined in three different ways, errors result which are associated with the determination of the areal extent of the four different basin categories and are on the order of 2-3 percent.

TABLE 4a

SNOW WATER EQUIVALENT
(Slope - Total Basin)

	Steep			Medium			Flat			Total
Elevation	1 SWE(m) (No. of obs)	2 Area (ha)	3 1x2 (m^3 x 10^3)	4 SWE(m) (No. of obs)	5 Area (ha)	6 4x5 (m^3 x 10^3)	7 SWE(m) (No. of obs)	8 Area (ha)	9 7x8 (m^3 x 10^3)	3+6+9 (m^3 x 10^3)
1	.480 (13)	35.7	171.4	.512 (8)	19.5	100.0	.491 (5)	19.8	97.1	368.5
2	.512 (19)	34.9	178.7	.778 (11)	19.7	152.9	.478 (6)	12.2	58.1	389.7
3	.753 (16)	64.4	485.1	.946 (10)	11.7	110.3	.717 (4)	4.5	32.5	627.8
4	.546 (12)	75.3	411.0	.169 (4)	2.4	4.1	1.272 (6)	2.9	37.1	452.1
	$\bar{X}$ = .567 (60)	Σ = 210.3	Σ = 1246.2	$\bar{X}$ = .691 (33)	Σ = 53.3	Σ = 367.3	$\bar{X}$ = .753 (21)	Σ = 39.4	224.7	Σ = 1838.1

TABLE 4b

SNOW WATER EQUIVALENT
(Aspect - Total Basin)

Elevation	Flat			North			South			East			Total
	1 SWE(m) (No. of obs)	2 Area (ha)	3 1x2 (m^3 x 10^3)	4 SWE(m) (No. of obs)	5 Area (ha)	6 4x5 (m^3 x 10^3)	7 SWE(m) (No. of obs)	8 Area (ha)	9 7x8 (m^3 x 10^3)	10 SWE(m) (No. of obs)	11 Area (ha)	12 10x11 (m^3 x 10^3)	3+6+9 +12 (m^3 x 10^3)
1	.491 (5)	19.7	96.5	.363 (8)	21.3	77.3	.560 (7)	19.8	110.8	.684 (6)	13.3	90.8	375.2
2	.478 (6)	12.5	59.6	.526 (10)	21.8	114.8	.578 (15)	27.6	159.5	1.049 (5)	4.5	46.8	380.7
3	.717 (4)	5.3	38.2	.546 (8)	27.8	152.0	.882 (10)	35.0	308.4	1.226 (8)	13.7	168.0	666.6
4	1.272 (6)	3.7	47.3	.294 (6)	31.5	92.6	.269 (4)	20.1	54.2	.835 (6)	25.0	208.6	402.8
	$\bar{X}$ = .753 (22)	Σ = 41.2	Σ = 241.6	$\bar{X}$ = .447 (32)	Σ = 102.4	Σ = 436.6	$\bar{X}$ = .624 (36)	Σ = 102.5	Σ = 632.8	$\bar{X}$ = .966 (25)	Σ = 56.4	Σ = 514.2	Σ = 1825.2

TABLE 4c

SNOW WATER EQUIVALENT
(Depth - Total Basin)

	Deep			Medium			Light			Total
Elevation	1 SWE(m) (No. of obs)	2 Area (ha)	3 1x2 (m^3 x 10^3)	4 SWE(m) (No. of obs)	5 Area (ha)	6 4x5 (m^3 x 10^3)	7 SWE(m) (No. of obs)	8 Area (ha)	9 7x8 (m^3 x 10^3)	3+6+9 (m^3 x 10^3)
1	.961 (5)	1.7	16.1	.506 (13)	49.2	248.8	.181 (8)	24.2	437.7	702.5
2	.839 (13)	10.8	90.5	.789 (12)	27.9	220.1	.130 (11)	28.0	36.4	347.1
3	1.354 (13)	10.9	147.7	.689 (12)	36.3	250.3	.027 (5)	33.4	9.0	407.1
4	1.791 (6)	8.8	157.7	.487 (8)	32.0	155.8	.114 (8)	39.8	45.4	358.9
	$\bar{X}$ = 1.191 (37)	Σ = 32.2	Σ = 412.0	$\bar{X}$ = .627 (45)	Σ = 145.4	Σ = 875.0	$\bar{X}$ = .123 (32)	Σ = 125.4	Σ = 528.5	Σ = 1815.5

TABLE 5a

SNOW WATER EQUIVALENT
(Slope - Upper Basin)

	Steep			Medium			Flat			Total
Elevation	1 SWE(m) (No. of obs)	2 Area (ha)	3 1x2 (m^3 x 10^3)	4 SWE(m) (No. of obs)	5 Area (ha)	6 4x5 (m^3 x 10^3)	7 SWE(m) (No. of obs)	8 Area (ha)	9 7x8 (m^3 x 10^3)	3+6+9 (m^3 x 10^3)
1	.480 (*)	3.5	16.7	.512 (*)	2.0	10.2	.600 (4)	17.7	106.4	133.2
2	.585 (17)	20.5	120.1	.864 (10)	15.3	132.3	.478 (6)	11.4	54.5	306.9
3	.779 (16)	53.3	414.9	.955 (10)	8.6	81.7	.717 (6)	.9	6.7	503.3
4	.565 (12)	69.9	395.1	.171 (4)	2.4	4.1	1.272 (6)	2.9	37.1	436.3
	$\bar{X}$ = .649 (45)	Σ = 147.2	Σ = 946.7	$\bar{X}$ = .786 (24)	Σ = 28.3	Σ = 228.3	$\bar{X}$ = .788 (20)	Σ = 33.0	Σ = 204.7	Σ = 1379.7

* No observations taken in upper basin; total basin data used

TABLE 5b

SNOW WATER EQUIVALENT
(Aspect - Upper Basin)

	Flat			North			South			East			Total
Elevation	1 SWE(m) (No. of obs)	2 Area (ha)	3 1x2 ($m^3 \times 10^3$)	4 SWE (m) (No. of obs)	5 Area (ha)	6 4x5 ($m^3 \times 10^3$)	7 SWE(m) (No. of obs)	8 Area (ha)	9 7x8 ($m^3 \times 10^3$)	10 SWE(m) (No. of obs)	11 Area (ha)	12 10x11 ($m^3 \times 10^3$)	3+6+9 +12 ($m^3 \times 10^3$)
1	.600 (4)	17.9	107.5	0	0	0	.560 (*)	.4	2.4	.684 (*)	2.9	19.5	129.4
2	.478 (6)	12.0	57.2	.539 (10)	15.5	83.5	.740 (12)	17.7	130.8	1.049 (5)	1.7	17.6	289.1
3	.717 (4)	3.3	24.0	.560 (8)	20.8	116.3	.917 (10)	31.6	290.0	1.226 (8)	8.2	101.1	531.4
4	1.272 (6)	3.7	47.3	.302 (6)	31.3	94.6	.279 (4)	20.1	56.2	.835 (6)	19.8	165.7	363.8
	$\bar{X}$ = .788 (20)	Σ = 37.0	Σ = 236.0	$\bar{X}$ = .487 (24)	Σ = 67.6	Σ = 294.4	$\bar{X}$ = .737 (26)	Σ = 69.9	Σ = 479.4	$\bar{X}$ = 1.056 (19)	Σ = 32.6	Σ = 303.8	Σ = 1313.6

TABLE 5c

SNOW WATER EQUIVALENT
(Depth - Upper Basin)

	Deep			Medium			Light			Total
Elevation	1 SWE(m) (No. of obs)	2 Area (ha)	3 1x2 (m^3 x 10^3)	4 SWE(m) (No. of obs)	5 Area (ha)	6 4x5 (m^3 x 10^3)	7 SWE(m) (No. of obs)	8 Area (ha)	9 7x8 (m^3 x 10^3)	3+6+9 (m^3 x 10^3)
1	.983 (2)	1.0	7.9	.479 (1)	17.7	84.6	.048 (1)	4.7	2.3	94.8
2	.839 (13)	10.8	90.5	.803 (12)	24.4	196.2	.163 (8)	12.0	19.6	306.3
3	1.354 (13)	10.9	147.7	.701 (12)	36.1	253.4	.027 (5)	15.7	4.2	405.4
4	1.791 (6)	8.8	157.7	.495 (8)	32.0	158.4	.114 (8)	34.5	39.3	355.3
	$\overline{X}$ = 1.212 (34)	Σ = 31.3	Σ = 403.9	$\overline{X}$ = .682 (33)	Σ = 110.2	Σ = 692.3	$\overline{X}$ = .109 (22)	Σ = 66.9	Σ = 65.4	Σ = 1161.8

Peak Accumulation

A survey of peak snow accumulation was made on May 18, 1973, and May 19, 1974, to determine depth and density of the 36 homogeneous units of the basin.

Density: Density measurements were taken with a Federal snow sampler at 17 of the 114 points of the snow course (Figure 1). Even through a relatively short elevational range (372 m) density was found to increase at a rate of 140 kg/m^{-3} per 1000 m. A summary of the snow density measurements taken at each of the stratifications is given in Table 6. Techniques used to determine depth and density are described in Appendix 1.

Snow water equivalent: The depth of snow water equivalent for each homogeneous area was derived as the product of the density and the mean depth of each of the elevational stratifications (Tables 4 and 5). Work on Marmot Creek from 1965-68 (Storr and Golding, 1973) indicates that snow water equivalent increases with elevation in forested areas. Data from Marmot Creek snow courses (which have an elevational range of 3000 m) suggest that snow water equivalent increases 62.8 cm per 1000 m. In the San Juan Mountains of southern Colorado, snow course data indicate that in the Rio Grande drainage snow water equivalent increases 110 cm per 1000 m while in the Colorado River drainage snow water equivalent increases 70 cm per 1000 m. Data from the Green Lakes Valley suggest that snow water equivalent increases 74.3 cm per 1000 m in the alpine even though the elevational range is 490 m.

The volume of snow water equivalent was derived as the product of snow water equivalent on a stratum and the area of the stratum (Bartos, 1972; Bartos and Richard, 1973). Tables 4a, 4b, and 4c give the volume of snow water equivalent at peak accumulation for each of the main categories of slope, aspect and depth for the entire basin. Tables 5a, 5b, and 5c give the snow water equivalent at peak accumulation for the categories of slope, aspect, and depth for the upper basin (i.e., the portion of the total basin which drains through D-4). Table 7 gives a summary of the proportion of snow water equivalent held on each stratification and the relative area of each stratification.

TABLE 6

SNOW DENSITY
1973, May 18

Stratification		Density (kg/m^3) (Number of obs)	Mean depth of density samples (cm)	Mean elevation of density samples (m)
Elevation	1	328 (3)	238	3479
	2	372 (5)	203	3622
	3	373 (6)	212	3719
	4	373 (3)	157	3790
Slope	Steep	358 (7)	174	3632
	Medium	359 (5)	222	3658
	Flat	381 (5)	230	3703
Aspect	Flat	381 (5)	230	3703
	North	345 (8)	177	3658
	South	376 (3)	220	3611
	East	410 (1)	246	3615
Depth	Deep	411 (6)	283	3682
	Medium	339 (10)	169	3634
	Light	346 (1)	87	3792
Total basin		365 (17)	203	3664

TABLE 7

SNOW WATER EQUIVALENT SUMMARY
(Total Basin)

	% swe	% area	% swe	% area	% swe	% area	% swe	% area
Elevation	1		2		3		4	
	26.4	24.7	20.3	22.0	31.1	26.7	22.2	26.6
Slope	Steep		Medium		Flat			
	67.8	69.4	20.0	17.6	12.2	13.0		
Aspect	Flat		North		South		East	
	13.2	13.6	23.9	33.9	34.7	33.9	28.2	18.6
Depth	Deep		Medium		Light			
	22.7	10.6	48.2	48.0	29.1	41.4		

SNOWPACK DEPLETION AND ABLATION

A great deal of work has been done on snowpack depletion from forested watersheds as a control of stream discharge (e.g. Leaf, 1967, 1969a, 1969b, 1971; Garstka, et al., 1958; Miller, 1953; and Parshall, 1941). Extrapolation from forested areas to alpine situations has been attempted (e.g. Golding, 1968a; Storr and Golding, 1973) but comparatively little work has previously been done directly on snowpack depletion and ablation from an alpine watershed (Bartos, 1972; Bartos and Richard, 1973a, 1973b; Martinelli, 1959a, 1959b, 1965, 1972, 1973; Kotlyekov, 1972; Santeford, 1973).

Method

Ablation measurements were taken at weekly intervals from June 16 to August 20, 1973, using the 114 snow course survey points as the sites of ablation stakes (Figure 1). Field techniques are described in Appendix 1.

Weekly contributions to the hydrograph from ablation were computed by summing the individual contributions of each of the homogeneous segments of the basin described above. The weekly contribution of each segment was derived as:

$$SWE = Abl \times Den \times SC \qquad (2)$$

where: SWE = snow water equivalent released (cm)

Abl = mean of weekly ablation (cm) for each segment

Den = mean basin density (Appendix 1)

SC = porportion of segment snow covered

Mean basin density is used rather than mean segment density because the regression of density at peak accumulation on elevation is not significant at the 95 percent level (Appendix 1). Further, the variation of snowpack density with elevation is probably less well marked after the pack becomes isothermal than it is before (U.S. Army, 1956).

Difficulties also arise in attempting to estimate areal changes in snow cover on a time scale equivalent to weekly ablation observations. A number of empirical relationships allow some estimation of snow cover changes but these, in turn necessitate the evaluation

of empirical basin characteristics. One such approach is to use the relationship of snow covered area to generated discharge (U.S. Army, 1956) which has the form:

$$A_s = 1.0 - \left(\frac{\sum Q_{gen}}{Q_{gen-total}}\right)^N \tag{3}$$

where: A_s = fractional portion of the basin area which is snow covered

Q_{gen} = generated discharge

$Q_{gen-total}$ = total seasonal generated discharge from the initial snow covered area

N = exponent expressing basin snow cover depletion with discharge

Discharge is expressed in terms of generated flows so storage effects are not pertinent. The value of N reflects the diversity of terrain effects on snow cover depletion. One difficulty with the relationship as expressed in equation (2) is the effect of subsequent summer precipitation on generated discharge. In practice, however, additional precipitation is negligible compared to generated discharge and is ignored here in estimating snow cover. A second difficulty lies in attempting to estimate snow cover from a parameter which is largely a function of snowpack volume. This, however, is accounted for in the exponential term N. Table 8 gives the changes in density (Appendix 1) and the fractional portion of the basin which is snow covered as derived from equation (3). Tables A1-3 and A1-4 (Appendix 1) give the weekly contribution of each of the forty basin segments in the main basin categories of elevation, slope, aspect, and depth. Tables A1-3 and A1-4 are summarized in Figure 2 which gives the relative weekly contribution of snow water equivalent from the four main basin categories.

Discussion: Figure 2 gives the percent depletion of the total snow water equivalent on each stratum of the upper basin during the nine week period in which ablation measurements were taken. Figure 2a gives the percent depletion of the elevation stratification of the upper basin. The total basin is stratified into four nearly equal parts; since the upper basin has a higher mean elevation than the total basin, elevation 1 contributes only 10.6% to the area of the

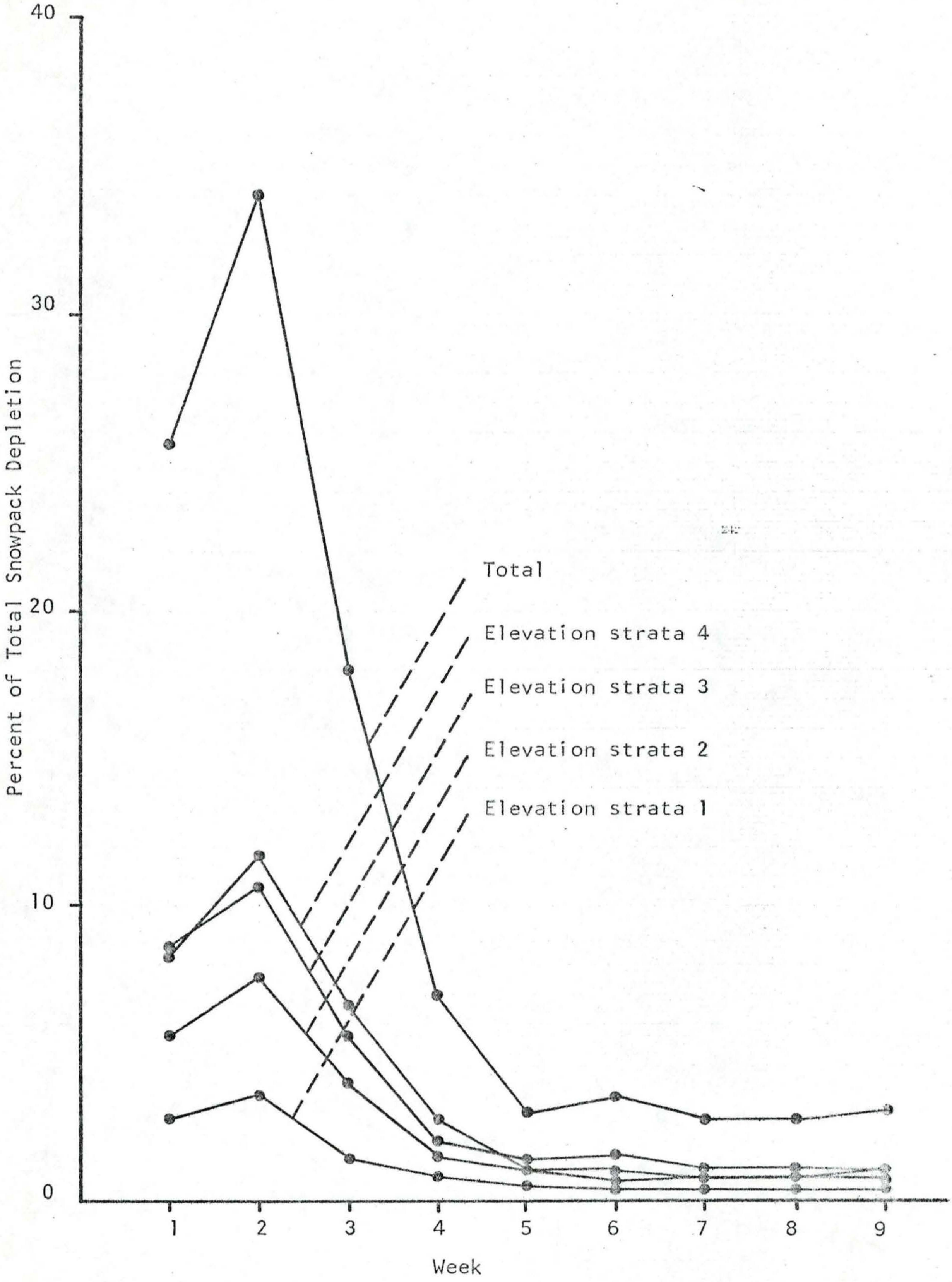
TABLE 8

DENSITY AND SNOW-COVER DEPLETION

Week Date	Density (kg/m^3)	Fractional portion of snow-cover
1 June 20 - 25	489	.81
2 June 25 - July 2	514	.67
3 July 2 - 9	539	.36
4 July 9 - 16	564	.18
5 July 16 - 23	590	.09
6 July 23 - 30	615	.08
7 July 30 - August 7	615	.07
8 August 7 - 13	615	.06
9 August 13 - 20	615	.05

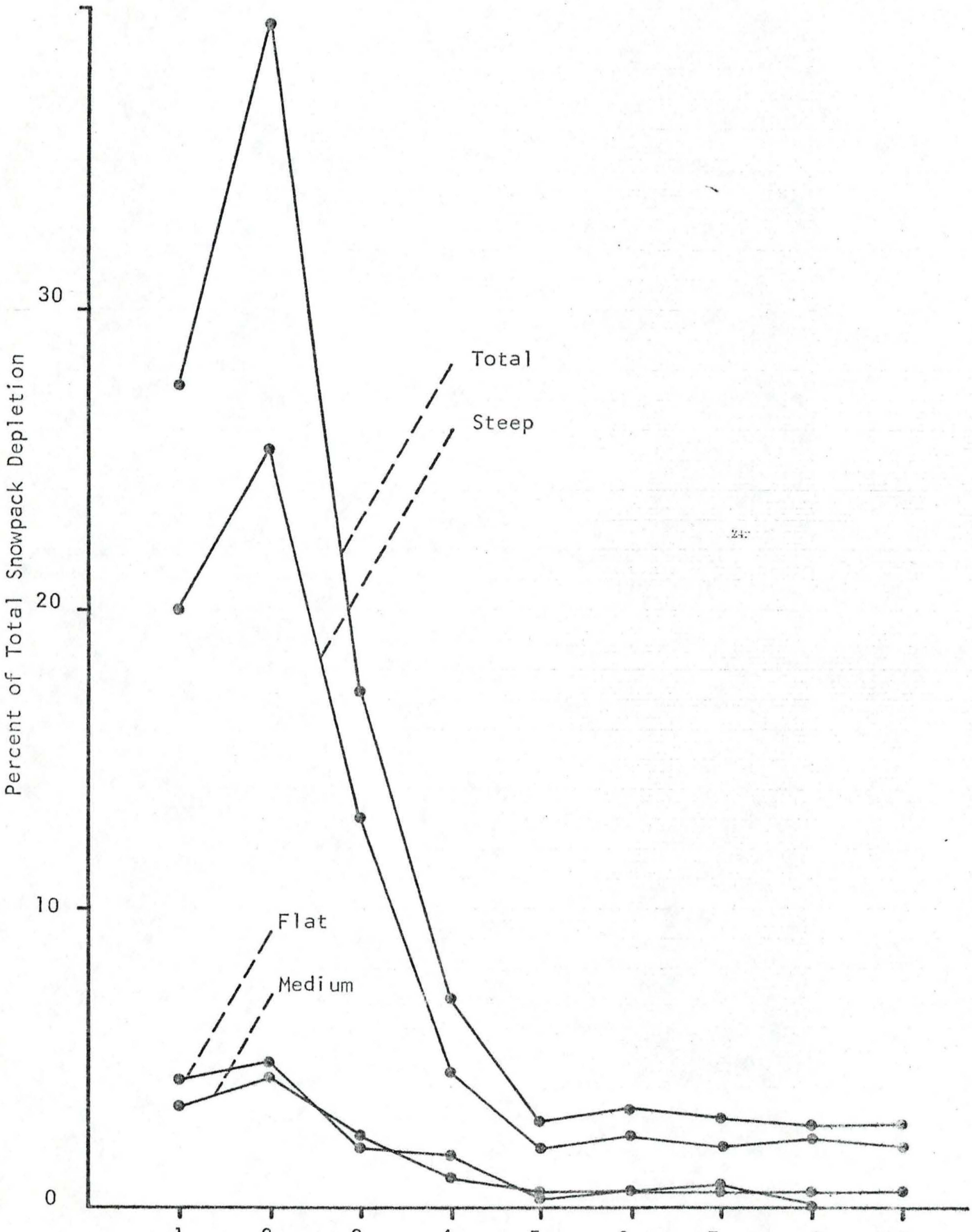
PERCENT SNOW WATER EQUIVALENT DEPLETION

Elevation - Upper Basin



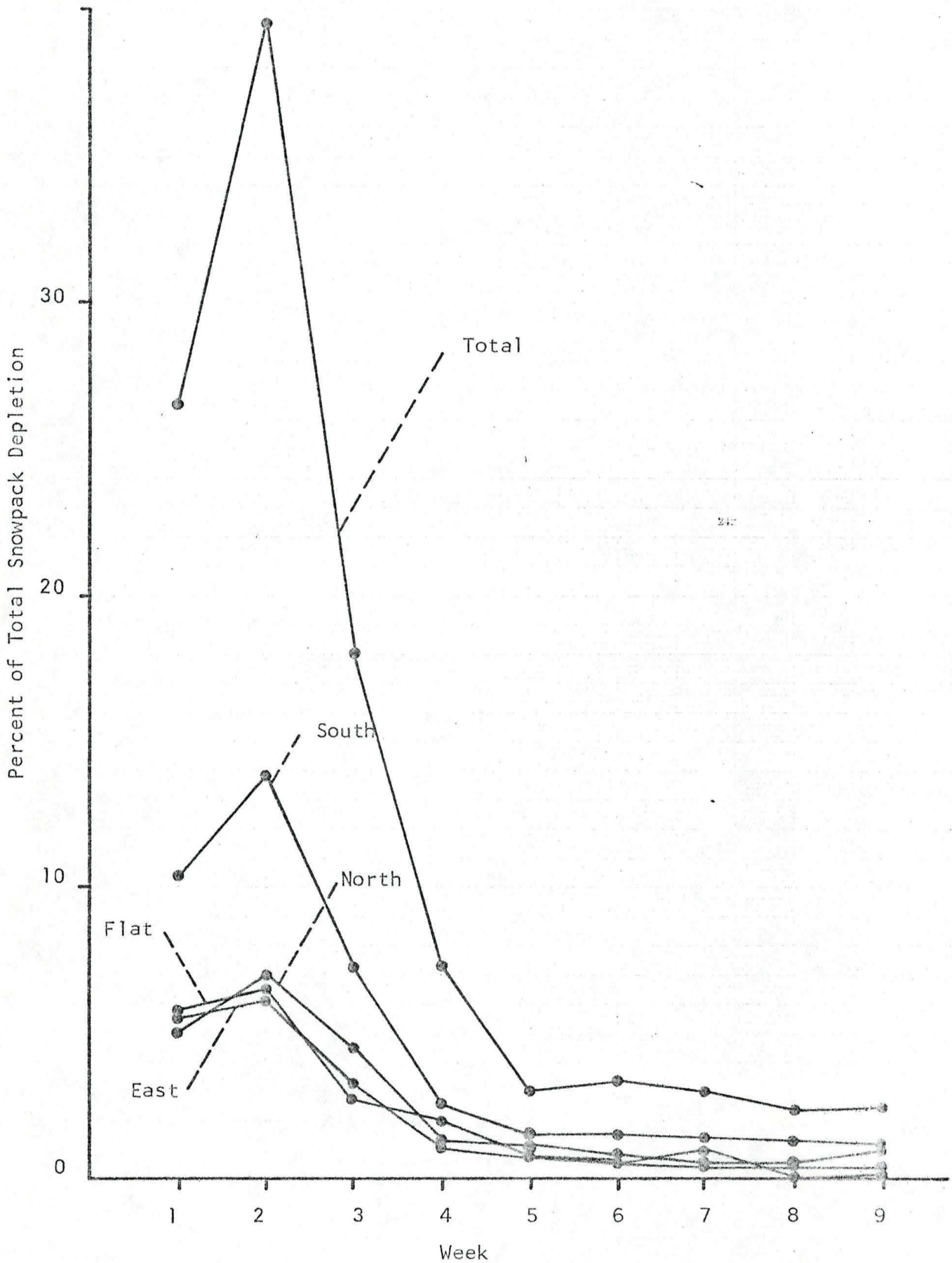
PERCENT SNOW WATER EQUIVALENT DEPLETION

Slope - Upper Basin



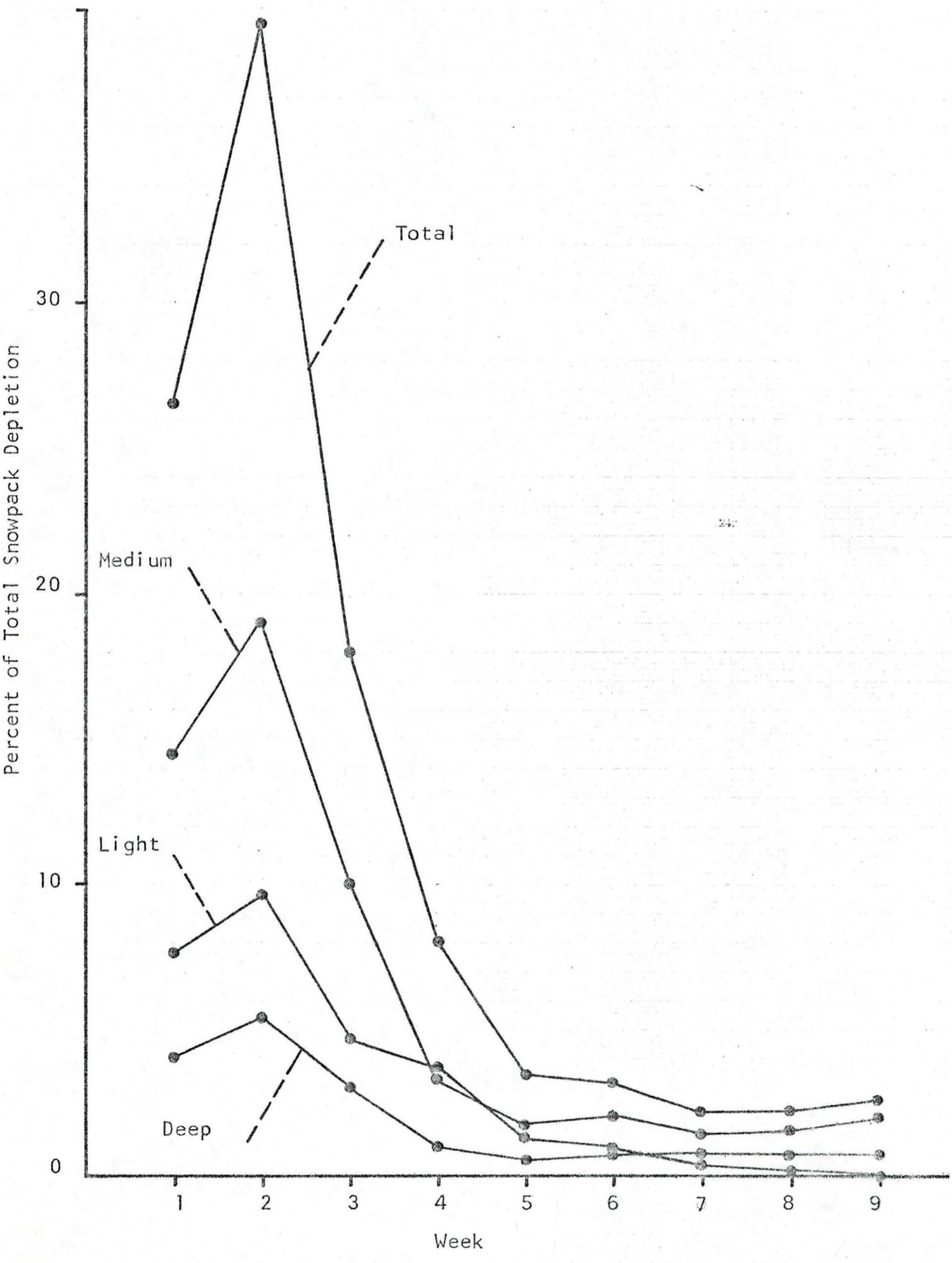
PERCENT SNOW WATER EQUIVALENT DEPLETION

Aspect - Upper Basin



PERCENT SNOW WATER EQUIVALENT DEPLETION

Depth - Upper Basin



upper basin while 24.7% of the total basin consists of elevation 1 (Tables 3 and 9). From Figure 2a it can be seen that during the first week (June 19-25), 25.7% of the total snow water equivalent in the upper basin ablated while only 5.7% of the total snow water equivalent ablated from elevation 2. Figure 2 indicates that during the second week (June 25 - July 2), approximately 34% of the total nine week's ablation took place. Figures 2a, 2b, 2c and 2d also indicate that most of the ablation took place on elevation 4; on steep, south facing slopes; and in areas of medium snow accumulation.

Table 9 suggests that these strata which contribute a large percent of the season's snow water equivalent are also the strata with the highest percent of the area in each of the four main categories. An efficient stratum can be defined as the one within each of the four main categories which has the highest percent ablation to percent area ratio (Table 9). The third elevation, steep slope, south aspect, and medium depth strata are the most efficient here with a maximum efficiency of 1.23. Efficiency is probably a function of snow accumulation patterns which may be influenced by meso-topography, local wind patterns, and ablation controls even though radiation patterns and medium snow depths are relatively uniform.

SUMMER PRECIPITATION

The snow survey of May 18 estimates the snow water equivalent on the basin at that time. Subsequent precipitation forms additional input to the water budget of the basin and is estimated here from a rigid-shielded eight inch recording rain gauge located at D-4 (3563 m, Figure 1). At windspeeds of 4.5 m sec^{-1} a rigidly shielded gauge underestimates rainfall by about 7% (Hamon, 1972) to 10% (Larson and Peck, 1974) and snowfall by 15 to 30 percent. At higher windspeeds (8.9 m sec^{-1}) the error increases to 25 percent for rain and 20-40 percent for snow. To take this into account, the actual summer precipitation at D-4 has been estimated as:

$$P_a = P_m/.93 \qquad (4)$$

TABLE 9

STRATUM EFFICIENCY
(Upper Basin)

Main Category	Strata	% of nine week melt	% total area	Efficiency
	1	10.7	10.6	1.01
Elevation	2	23.1	23.0	1.00
	3	32.0	30.6	1.05
	4	34.2	36.5	0.94
	Steep	73.4	70.6	1.04
Slope	Medium	12.9	13.6	0.95
	Flat	13.7	15.8	0.87
	Flat	18.8	17.7	1.06
Aspect	North	21.5	32.4	0.66
	South	41.1	33.5	1.23
	East	18.6	15.6	1.19
	Deep	16.1	15.0	1.07
Depth	Medium	55.7	52.9	1.05
	Light	28.2	32.1	0.88

$\overline{X} = 1.00$

where: P_a = actual precipitation

P_m = measured precipitation

This results in an estimate of 32.48 cm of precipitation for the period of May 18 to October 31, 1973. Daily precipitation totals are summarized in Table A2-1 (Appendix 2).

The representativeness of the D-4 recording gauge data as an estimate of precipitation over the entire basin can be evaluated from the data of Barry (1972, p. 104). This involves precipitation records at 14 locations within the upper basin taken at four 28-day intervals during the summer of 1969 which show a summer mean of 17.44 cm and a standard deviation of 1.23 cm indicating little variation in precipitation between gauge sites. A between-gauge analysis of variance on the 1969 data shows no significant differences between the 14 sites. Consequently, weekly precipitation input to the basin is derived as the product of the corrected weekly total precipitation recorded at D-4 and the basin area. Errors are introduced by this method when figuring precipitation on a short term basis; for example, a storm which deposits precipitation over the upper most portion of the basin may not be recorded at D-4. However, the effect is probably random over the basin. This type of error will be introduced when computing basin precipitation at weekly intervals; however, it will be minimized when computing seasonal precipitation as sample size increases. Table 10 gives the summer precipitation data and volume input from May 19 to October 31 for both the upper basin and the total basin.

CONCLUSION

The largest input to an alpine water budget is that of winter accumulation. At peak accumulation in May, $1.8 \times 10^6/m^3$ (60.47 cm) of snow water equivalent was held on the entire basin while $1.3 \times 10^6/m^3$ (67.63 cm) was held on the upper basin. During the summer, water is released from the snowpack to form the primary input to the seasonal water budget. In order to estimate the volume of input from the winter snowpack on a weekly basis an estimate of ablation and snow cover are necessary. Ablation measurements were made at weekly intervals while an estimate of snow cover was derived empirically from generated discharge. The product of ablation and

TABLE 10

SEASONAL PRECIPITATION

Week Date	Precipitation (cm)	Volume over total basin ($m^3 \times 10^3$)	Volume over upper basin ($m^3 \times 10^3$)
May 19 - 21	.76	22.9	14.7
May 22 - 28	1.57	47.4	30.4
May 29 - June 4	5.71	172.9	110.9
June 5 - 11	0.0	0.0	0.0
June 12 - 18	2.68	81.0	52.0
June 19 1 - 25	0.0	0.0	0.0
June 26 2 - July 2	.62	18.7	12.1
July 3 3 - 9	1.24	37.4	24.0
July 10 4 - 16	4.17	126.3	81.1
July 17 5 - 23	2.51	76.1	48.8
July 24 6 - 30	1.44	43.6	28.0
July 31 7 - Aug 6	1.92	58.2	37.3
Aug 7 8 - 13	.14	4.1	2.7
Aug 14 9 - 20	1.08	32.8	21.1
Aug 21 - 27	2.13	64.4	41.3
Aug 28 - Sept 3	.30	9.1	5.9
Sept 4 - 10	1.10	33.2	21.3
Sept 11 - 17	.71	21.6	13.9
Sept 18 - 24	0.0	0.0	0.0
Sept 25 - Oct 1	3.71	112.4	72.1
Oct 2 - 8	.14	4.2	2.7
Oct 9 - 15	.55	16.6	10.7
Oct 16 - 22	0.0	0.0	0.0
Oct 23 - 29	0.0	0.0	0.0
Oct 30 - 31	0.0	0.0	0.0
Total Season	32.48	983.1	630.8

snow cover at weekly intervals gives a rough estimate of the volume of input to the water budget during the interval. The estimate of areal snow cover probably introduces most of the error into the weekly estimate of volume input.

Additional input to the water budget is summer precipitation. Precipitation recorded at D-4 was used as an estimate of the basin precipitation. Weekly estimates of input from precipitation may be in error since areal variation of basin precipitation will not be compensated for in the short term. However, errors associated with areal variation of precipitation are minimized over the season. Consequently, the error of the precipitation term in the seasonal water budget is acceptably low. A summary of the inputs to the water budget is given in Table 11.

TABLE 11

SUMMARY OF INPUT TO WATER BUDGET

Week Date	Upper basin (D-4) Snow-melt input (cm)	Precip-itation (cm)	Total (cm)	Lower basin (Albion) Snow-melt input (cm)	Precip-itation (cm)	Total (cm)
1 June 19 - 25	17.88	0.0	17.88	15.45	0.0	15.45
2 June 26 - July 2	22.93	.62	23.55	20.84	.62	21.46
3 July 3 - 9	11.69	1.24	12.93	10.49	1.24	11.73
4 July 10 - 16	4.96	4.17	9.13	4.23	4.17	8.40
5 July 17 - 23	2.00	2.51	4.51	1.94	2.51	4.45
6 July 24 - 30	2.17	1.44	3.61	1.97	1.44	3.41
7 July 31 - Aug 6	1.82	1.92	3.74	1.58	1.92	3.50
8 Aug 7 - 13	1.53	.14	1.67	1.48	.14	1.62
9 Aug 14 - 20	1.56	1.08	2.64	1.42	1.08	2.50
Total of 9 weeks	66.54	13.12	79.66	59.40	13.12	72.52

Total snow water equivalent at peak accumulation (1973, May 18)
Total basin 60.47 cm
Upper basin 67.63 cm

Total seasonal precipitation May 19; Oct 31 32.48 cm

CHAPTER III

OUTPUT TO SEASONAL WATER BUDGET

Output of the water budget is considered to occur primarily in two ways: stream discharge and evapotranspiration. Stream discharge is usually the most accurately measured parameter of a water budget and consequently may be used as a check on the other less accurately measured parameters (Storr, 1973).

STREAM DISCHARGE

Stream discharge was measured at two locations in the Green Lakes basin: D-4 and Albion (Fig. 1). The four foot Parshall flume at the Albion location (3350 m) is at tree line and drains the 3.02 km^2 alpine environment. D-4 (3554 m) is a natural section which drains the upper 64.3% of the basin. In 1973, the stream discharge record runs from June 19 (D-4) and June 15 (Albion) to October 29. At both stations, the record begins approximately 2 days after flow began and a linear extrapolation backwards will be used to estimate streamflow on these days. Figure 3 and Table A2-1 (Appendix II) show the season's observed hydrograph at both D-4 and Albion. Appendix III gives the 1974 daily stream discharge measurements. Appendix II describes the techniques used in establishing a rating curve and estimating volume of discharge at a given stage.

HYDROGRAPH ANALYSIS

Classical streamflow hydrograph analysis has been discussed by Linsley, et al., (1949), Chow (1964), and Wilson (1969). The special case in which the discharge is derived largely from snowmelt has been discussed by the U.S. Army (1956, 1961), Garstka, et al., (1958) and Leaf (1969) and is of most relevance here.

Traditionally it has been assumed that surface runoff produces the rise and generally the greatest volume of streamflow from a given runoff event (e.g. Hursh and Brater, 1941). Hewlett and

FIGURE 3a

1973 OBSERVED HYDROGRAPH

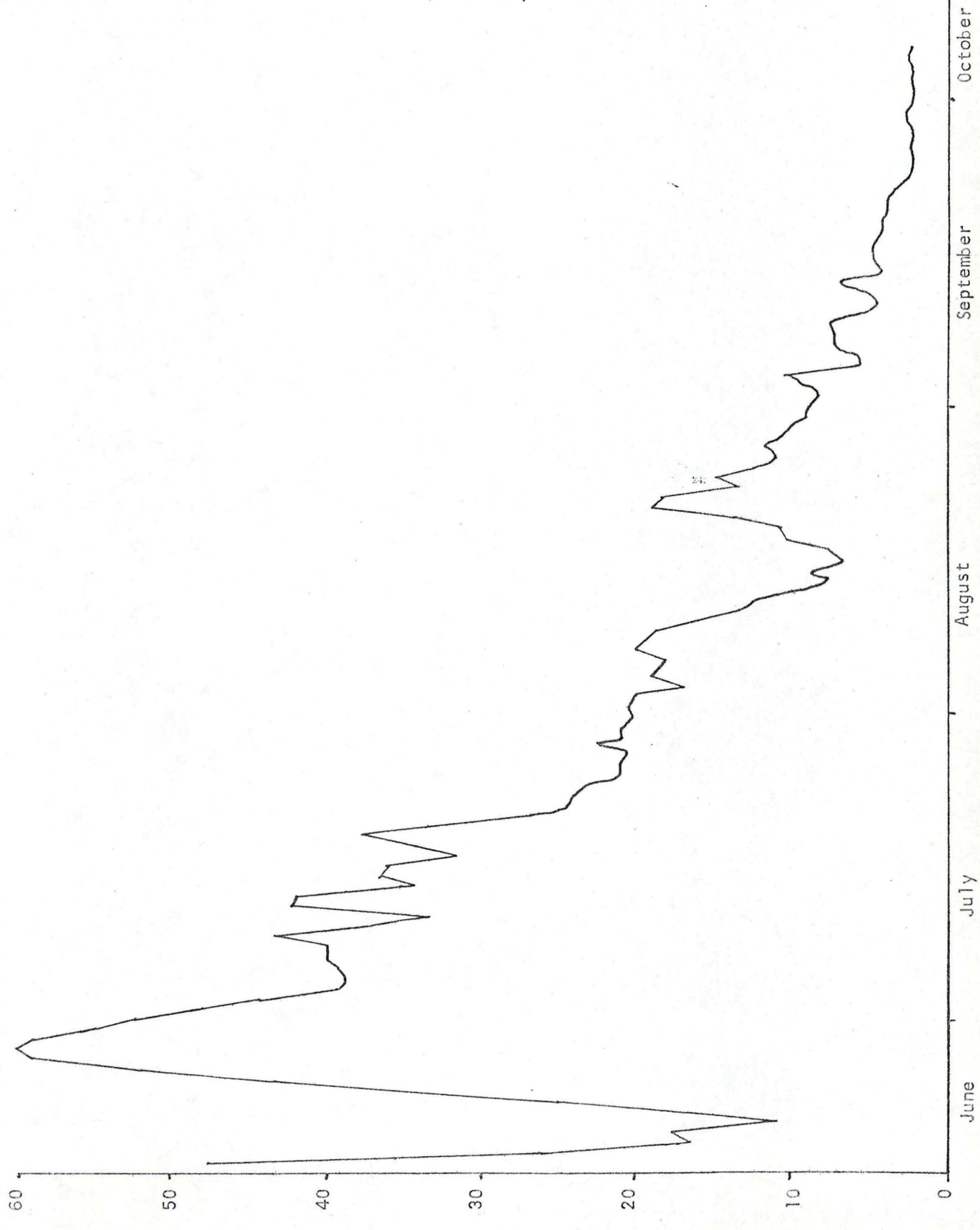
D-4
($m^3 \times 10^3$)

FIGURE 3b

1973 OBSERVED HYDROGRAPH

Albion

($m^3 \times 10^3$)



Hibbert (1967) have challenged this view by suggesting that subsurface flow is primarily responsible for the flood hydrograph. "In the forested watersheds of the Rocky Mountains, there is no watershedwide surface runoff from snowmelt. Practically all of the snowmelt runoff enters stream channels as subsurface or groundwater flow" (Leaf, 1969b, p. 30). Consequently, the water yield of a stream basin is largely the summation of daily increments of discharge through a number of porous media (Bertle, et al., 1950). In the alpine environment a similar model is probably applicable although the characteristics of the media involved may be different from those in forested areas. In particular, the presence of large areas of open talus and bare bedrock should lead to faster responses in the alpine.

Because virtually all of the water from snowmelt enters the stream as subsurface flow, there is a significant delay of runoff. The streamflow-recession concept provides an indirect means of evaluating this delay in relation to outflows from the watershed. For present purposes, the recession concept can be defined by assuming that all input to a basin is suddenly stopped, then the subsequent outflow from the basin would result solely from storage depletion and should follow an approximately logarithmic decay curve through time. The volume of this recession flow, (i.e. the integral of the decay curve) is therefore a measure of the storage capacity of the watershed (Leaf, 1969b). It is an important characteristic of the basin.

Green Lakes Recession Analysis

The recession curve is described by a simple decay function:

$$Q_t = KQ_{t-1} \tag{5}$$

$$= K^t Q_o \tag{6}$$

where: Q_o = the stream flow

t = time counted from $T = 0$, the start of the recession

K = a recession constant which is less than 1

(Garstka, et al., 1958; Chow, 1964; Leaf, 1969b; Wilson, 1969)

Empirical estimates of the recession coefficients were derived both for D-4 and Albion from the 1973 data as:

$$K = \frac{\sum\left(\frac{Q_t}{Q_t-1}\right)}{N} \qquad (7)$$

where: Q = discharge

t = day number

N = number of cases

In making this estimate, only occasions in which no precipitation occurred on day t or on the two preceding days were used. This gives some assurance that a recession flow is, in fact, being observed. At D-4 N equals 53; at Albion N equals 33. The Albion record is not as long because at the end of the season discharge dropped below the level in which it could be measured precisely in the flume (Table A2-1). At D-4 the recession coefficient is a function of discharge:

$$K = .97695 - (1.679 \times 10^{-6})\ Q \qquad (8)$$

where Q is measured in $m^3\ day^{-1}$. Initially, the b term of equation (8) seems small; however, Q is of the range from $50 \times 10^3\ m^3$ to $20 \times 10^3\ m^3$ while a Q of $23.5 \times 10^3\ m^3$ is necessary to vary K by one standard error. Equation (8) is significant at the 95% level and the standard error of the estimate equals .0394. However, at Albion, the value of the recession coefficient was found to be constant with discharge and equal to .93787 (Fig. 4). A difficulty arises in determining whether or not K is a function of Q by the least squares method. In regressing $\frac{Q_t}{Q_{t-1}}$ on Q_t the assumption of the physical independence of the two variables has been violated. In an attempt to compensate for this violation $\frac{N}{2}$ degrees of freedom are used in the significance test. The D-4 regression is significant at the 95% level using the reduced degrees of freedom while the Albion regression is not. The fact that the recession coefficient is related to discharge at D-4 and has no relation to discharge at Albion is undoubtedly related to the basin routing. Streamflow at D-4 is routed through only two lakes while streamflow at Albion is routed through four lakes.

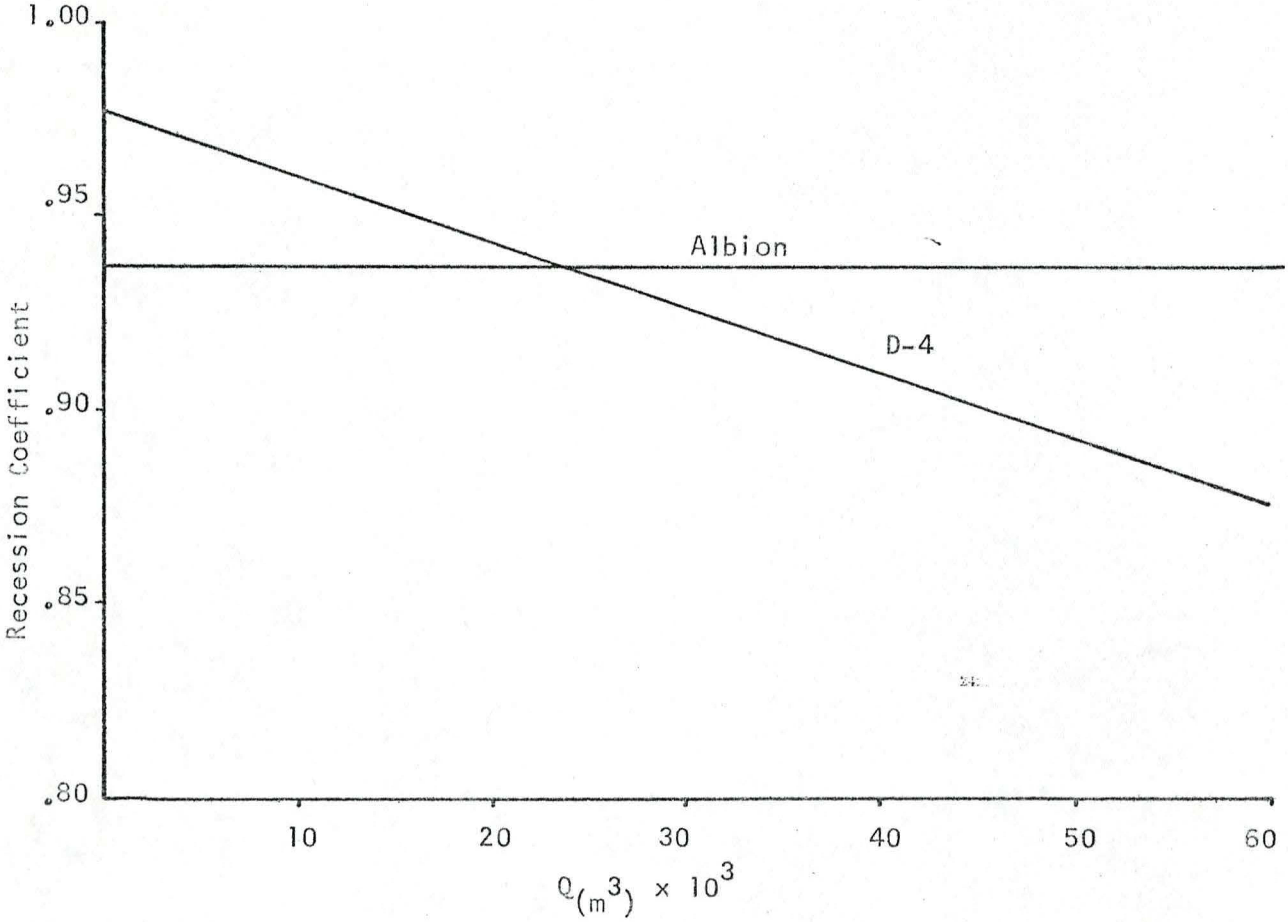


FIGURE 4

VARIATION OF RECESSION COEFFICIENT WITH DISCHARGE

$$K_{alb} = .93787$$

$$K_{D-4} = .97695 - (1.679 \times 10^{-6})\, Q_{(m^3)}$$

The storage volume remaining in the basin at any time was determined by integrating the two recession curves to give volume to flow curves. These relate discharge to the remaining runoff volume beneath the recession curve and above an assumed constant base flow of .01477 m^3/second at D-4 and .02274 m^3/second at Albion. Discharge at the end of October was used as an estimate of base flow at both locations.

The volume in storage can also be expressed by the Muskingum equation (McCarthy, 1938; Chow 1964; Wilson, 1969) for storage:

$$S = T_s \left[XI + (1-X)Q \right] \tag{9}$$

where: T_s = the storage constant

X = the relative importance of inflow and outflow in determining storage

I = the inflow to storage

Q = the outflow from storage

The term T_s is the ratio of storage to discharge and has the dimension of time. It approximates the average travel time through the storage reservoir. For a small reservoir, the storage volume equivalent to a given outflow is about the same whether the stage is rising or falling; consequently, X equals 0.0 (Leaf, 1969b). This defines storage as a function of outflow alone and so equation (9) reduces to:

$$S = QT_s \tag{9a}$$

The variation of storage time (T_s) with outflow was derived for D-4 and Albion by using equation (9a) and the storage curves of Figure 5. This relationship is given in Figure 6.

GENERATED DISCHARGE

Generated discharge is defined as the volume of streamflow at either gauging point produced by snowmelt. It is derived as the flow resulting from the melt contribution of one snowmelt day. A snowmelt day is the period of time from one trough in the snowmelt hydrograph to the next trough which normally occurs 24 hours later (U.S. Army 1956, 1961; Garstka, et al., 1958; Leaf 1969b, 1971; Haeffner and Leaf 1973).

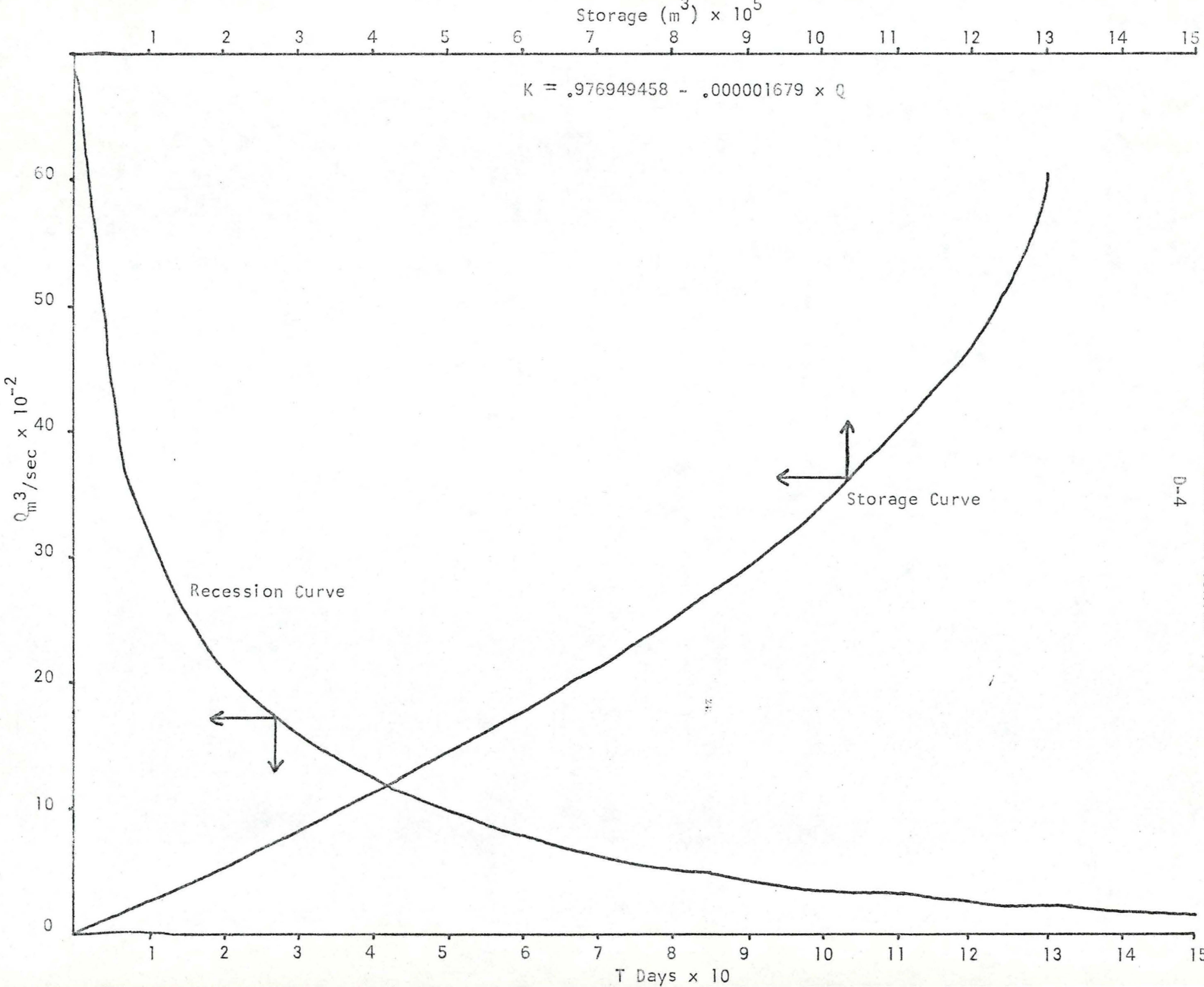
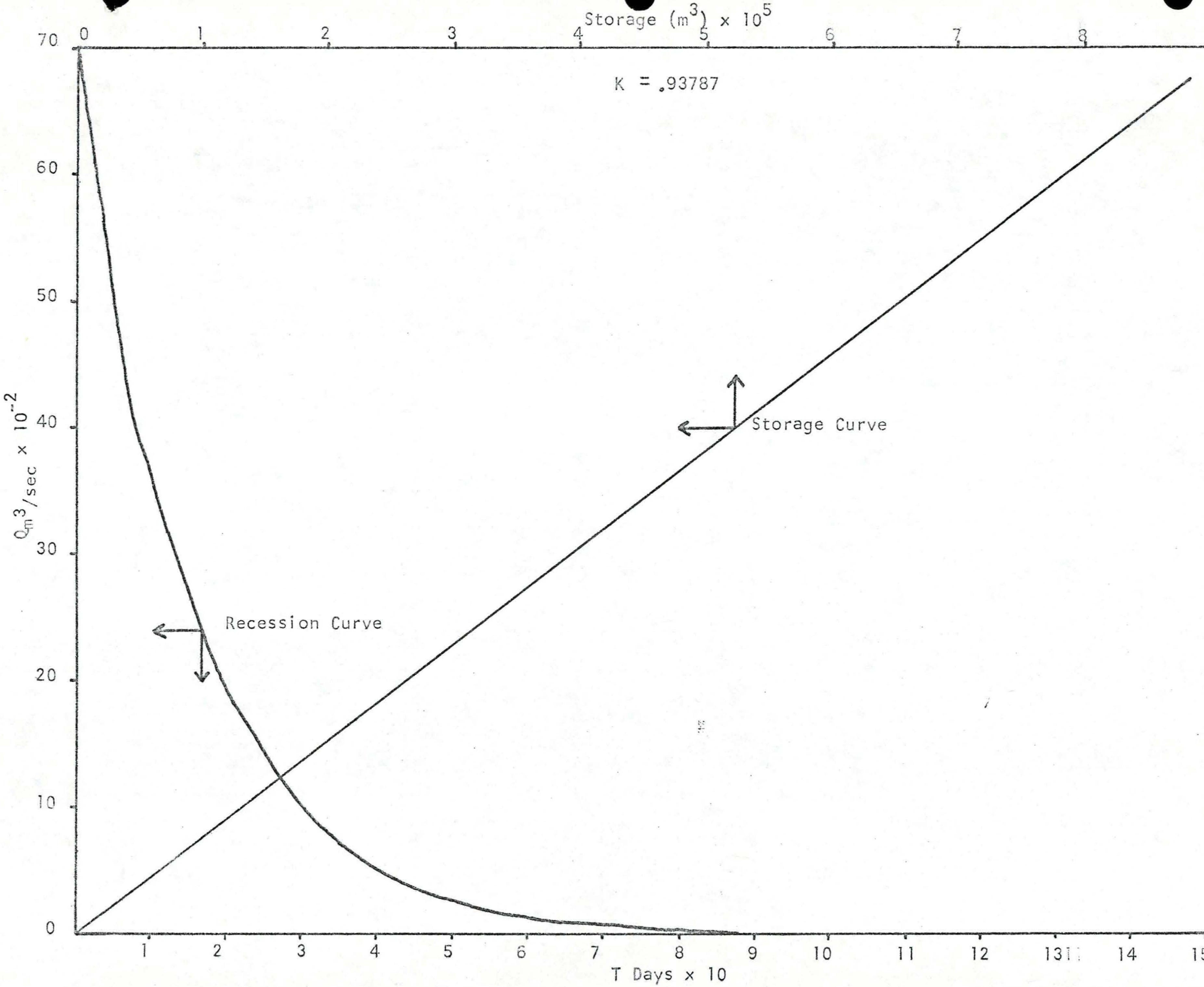


FIGURE 5a

STORAGE AND RECESSION CURVES

D-4



STORAGE AND RECESSION CURVES

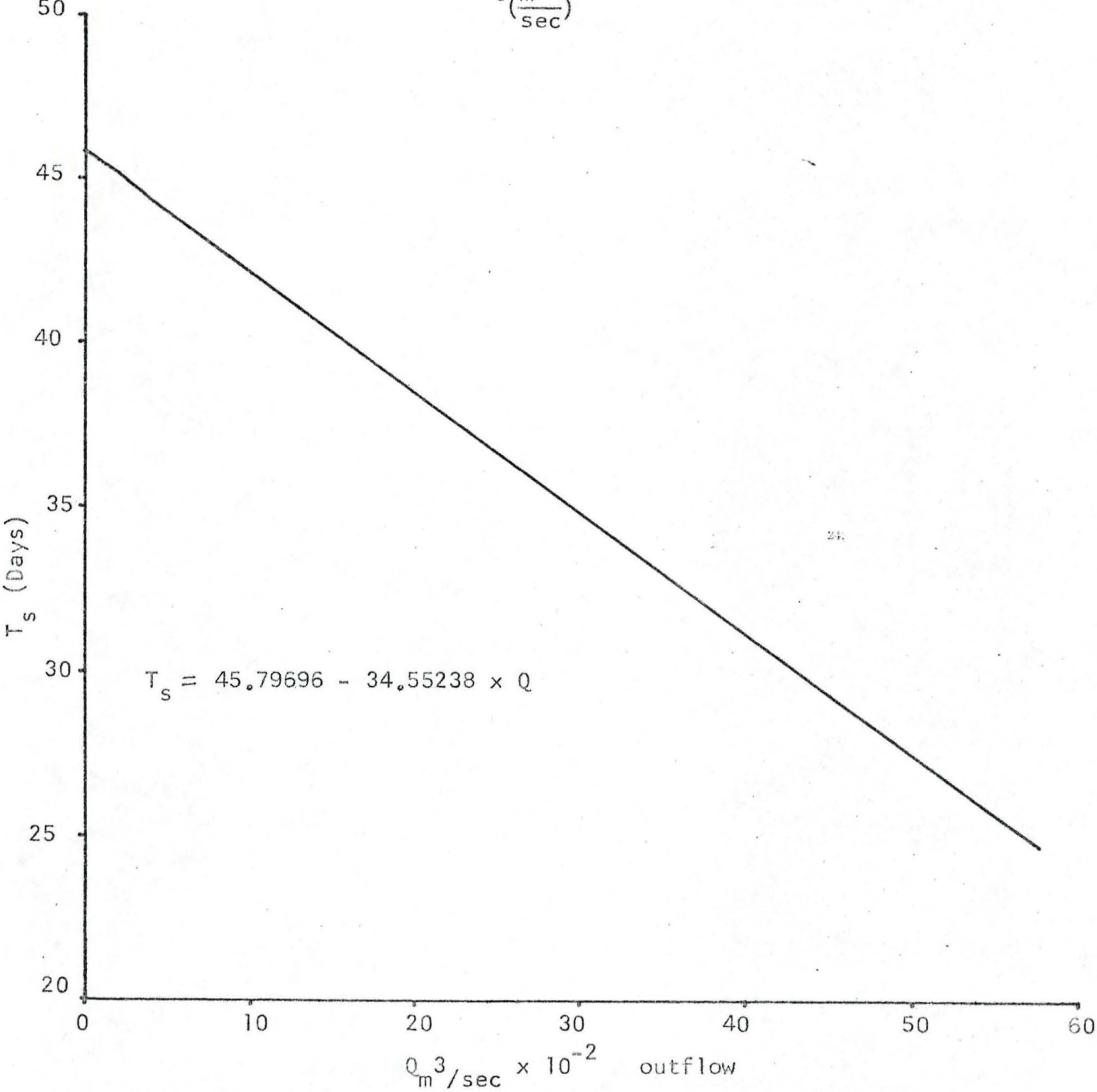
Albion

FIGURE 5b

VARIATION OF STORAGE TIME WITH OUTFLOW

D-4

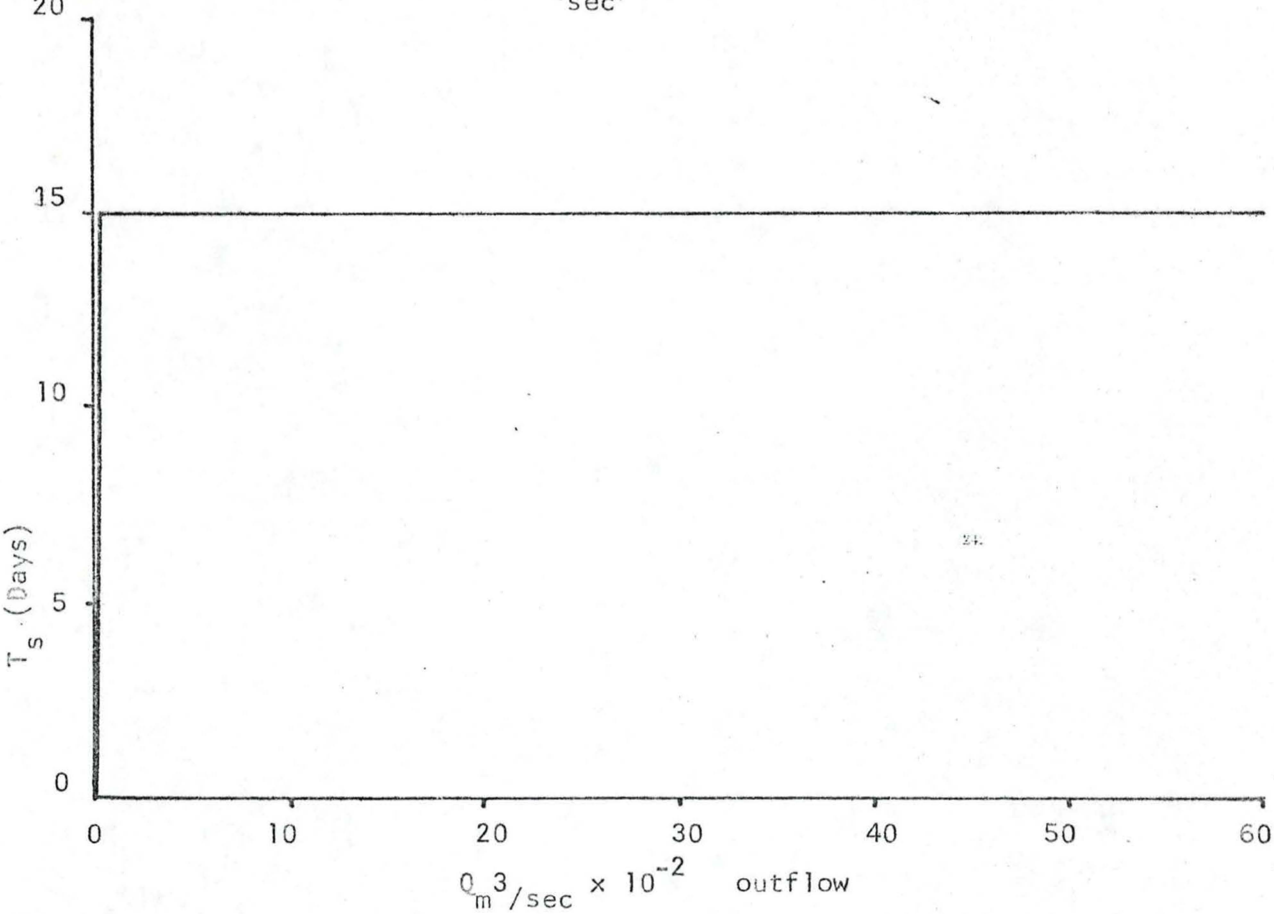
$$T_s = \frac{S_{t(m^3)}}{Q_{t(\frac{m^3}{sec})} \times 86400}$$



VARIATION OF STORAGE TIME WITH OUTFLOW

Albion

$$T_s = \frac{S_{t(m^3)}}{Q_{t\left(\frac{m^3}{sec}\right)} \times 86400}$$



In this study, the net flow generated from each snowmelt week (i.e., seven snowmelt days) was isolated on the discharge hydrograph by means of the recession curve (U.S. Army, 1956). Other workers have estimated the generated flow for each snowmelt day (Leaf, 1969b; U.S. Army, 1956; Garstka, et al., 1958) but this requires a more precise estimate of the recession coefficient than is available here. Each week corresponds to the weeks in which ablation measurements were made throughout the basin (June 19 to August 20).

Generated runoff volumes (Q_{gen}) from D-4 were computed from observed daily runoff volumes by equation (10):

$$Q_{gen} = Q_{obs} + STG2 - STG1 \tag{10}$$

where: Q_{obs} = the observed runoff during the snowmelt week

STG1 = the initial volume of storage on the watershed at the beginning of the snowmelt week

STG2 = the terminal volume of storage on the watershed at the end of the snowmelt week

This procedure is given schematically in Figure 7. Storage is used here as groundwater or basin storage and specifically excludes lake or snowpack storage. The terms for the volume in storage (STG1 and STG2) are a function of the discharge rate and are derived from the recession analysis. Table 12 gives the summary of the generated discharge at weekly intervals.

Difficulties arise with the concept of generated discharge. From equation (10) it can be seen that if the volume in storage at the end of a snowmelt week (STG2) plus the observed flow during the snowmelt week (Q_{obs}) is less than the volume in storage at the beginning of the snowmelt week (STG1) a negative generated discharge (Q_{gen}) will result. This can be interpreted as a flow from basin storage. During the spring, Q_{gen} normally exceeds Q_{obs} with the excess going to groundwater recharge. Late in the season, the situation reverses with Q_{obs} greater than Q_{gen} and the excess flowing from groundwater storage. An extreme case of this occurs when generated discharge is negative. Over a long period of time (a water year) of course, the two terms (Q_{gen} and Q_{obs}) should be about equal.

$$Q_{gen} = Q_{obs} + STG2 - STG1$$

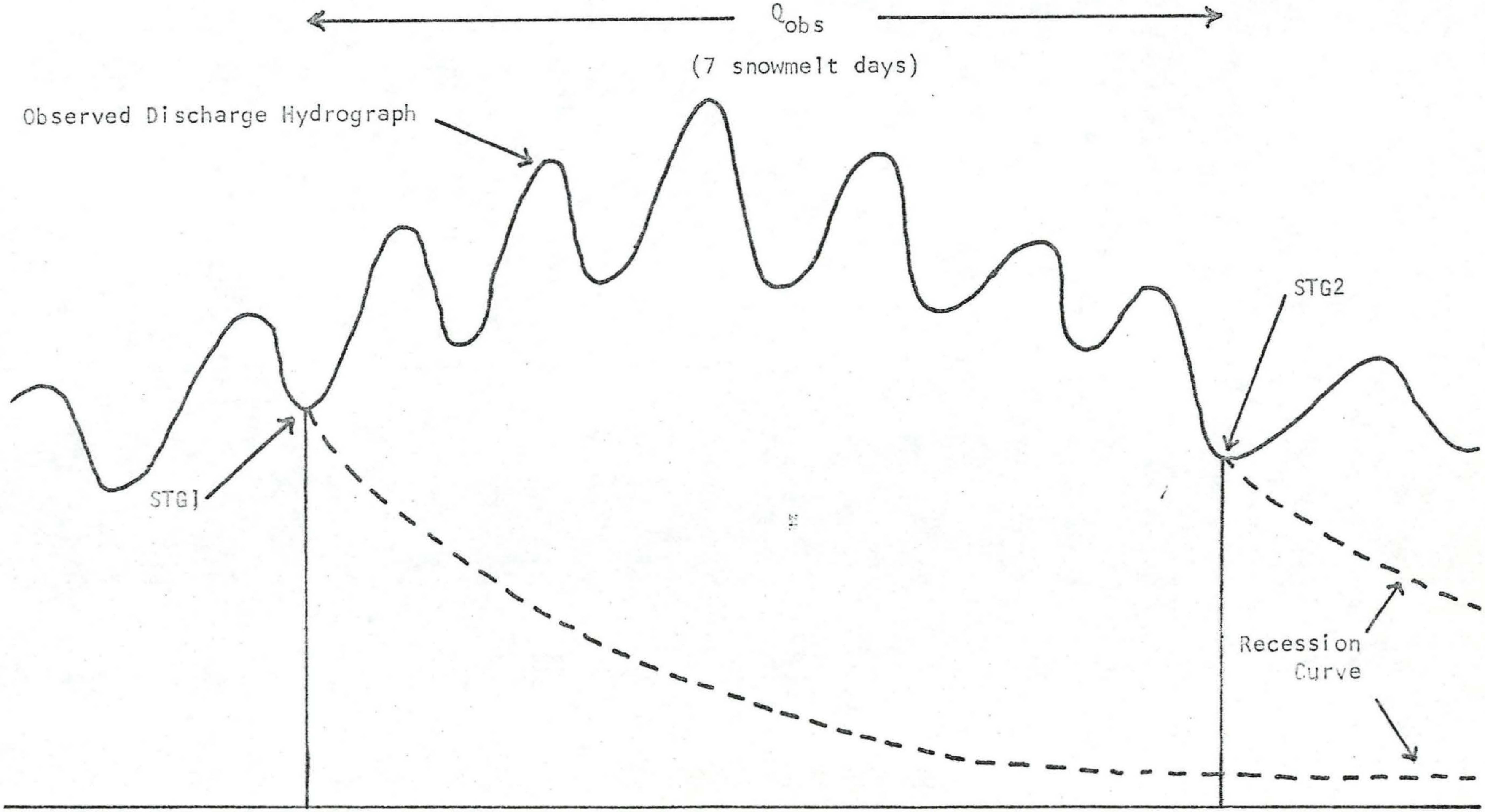


FIGURE 7

GENERATED DISCHARGE

TABLE 12a

D-4 GENERATED DISCHARGE

Week End Date	Q_{gen} ($m^3 \times 10^3$)	Q_{obs} ($m^3 \times 10^3$)	Stg 2 ($m^3 \times 10^3$)	Stg 1 ($m^3 \times 10^3$)
1 June 26	844.2	105.6	1129.0	390.4
2 July 3	146.3	335.7	939.6	1129.0
3 July 10	214.7	190.0	964.2	939.6
4 July 17	157.9	211.3	910.9	964.2
5 July 24	-129.6	160.0	621.3	910.9
6 July 31	130.2	120.5	631.0	621.3
7 Aug. 7	134.5	103.9	661.6	631.0
8 Aug 14	-116.5	93.5	451.6	661.6
9 Aug 21	165.8	88.4	529.0	451.6
Aug 28	- 17.4	89.6	422.0	529.0
Sept 4	-124.3	54.6	243.1	422.0
Sept 11	67.6	34.8	276.0	243.1
Sept 18	- 10.2	49.1	216.7	276.0
Sept 25	- 16.8	27.8	172.2	216.7
Oct 2	- 1.8	25.0	145.4	172.2
Oct 9	5.0	19.6	130.8	145.4
Total	1449.7	1709.3		

TABLE 12b

ALBION GENERATED DISCHARGE

Week End Date	Q_{gen} ($m^3 \times 10^3$)	Q_{obs} ($m^3 \times 10^3$)	Stg 2 ($m^3 \times 10^3$)	Stg 1 ($m^3 \times 10^3$)
June 19	-367.7	116.8	137.2	621.6
1 June 26	757.4	157.8	736.8	137.2
2 July 3	298.3	413.1	622.0	736.8
3 July 10	173.8	260.7	535.1	622.0
4 July 17	235.5	258.4	512.2	535.1
5 July 24	139.3	255.0	326.5	512.2
6 July 31	134.2	146.9	313.8	326.5
7 Aug 7	74.7	126.2	262.4	313.8
8 Aug 14	- 68.0	105.9	88.5	262.4
9 Aug 21	155.7	64.6	179.6	88.5
Aug 28	53.9	96.3	137.2	179.6
Sept 4	2.1	64.0	75.3	137.2
Sept 11	33.2	41.3	67.2	75.3
Sept 18	28.9	33.3	62.8	67.2
Sept 25	- 2.1	20.8	39.8	62.8
Oct 2	7.8	18.0	29.6	39.8
Total	1556.9	2149.0		

A second difficulty with the concept of generated discharge is its dependence on the empirical estimate of the recession coefficient. Normally, several years of discharge data would be used in establishing this parameter but this has not been possible here. The imprecision of the recession coefficient will contribute to the imprecision of generated discharge estimate.

EVAPOTRANSPIRATION

Evapotranspiration is the second output of the water budget (Storr, 1973; Storr and Golding, 1973; Hamon, 1966; Harris, 1972; Ward, 1972). This includes evaporation from rock, stream, lake, and soil surfaces as well as the volume of transpiration from the vegetation in the basin. Different plant types transpire at different rates (Thornthwaite, 1948) while moisture evaporates at different rates from the different surface types within the basin. Evaporation and transpiration are combined and an attempt is made to compute potential and actual evapotranspiration within the basin. Several different methods have been used to estimate potential evapotranspiration (Thornthwaite, 1948; Blaney, 1952; Penman, 1956). The Thornthwaite method is considered to give a good seasonal estimate (Hamon, 1963; Kakela, 1973) but was not used in this study because only a mean monthly value of potential evapotranspiration for months with a mean temperature above 0° C. From Hamon (1963), potential evapotranspiration can be computed as:

$$PE = C D^2 P_t \qquad (11)$$

where: P.E. = average potential evapotranspiration in inches per day

D = possible hours of sunshine in units of 12 hours

P_t = saturated water vapor density (absolute humidity) at the daily mean temperature in grams per cubic meter times 10^{-2}

C = .55 chosen to give appropriate yearly values of potential evapotranspiration as indicated by observations reported in the literature

Equation (11) allows an estimate of potential evapotranspiration for the basin but this is only useful in the parts of the basin with a nonlimiting supply of water (Thornthwaite, 1948). Consequently. the basin was divided into three areas based on the vegetation

mapping by Keammerer and Webber (1974): (1) areas where water is not limiting (e.g. lakes; areas of willows and bogs), (2) areas of tundra vegetation, and (3) areas of bare rock (e.g. bedrock and talus). Table 13 gives the relative proportions of each of the three categories within the basin. Actual evapotranspiration for the wet areas was assumed the same as potential evapotranspiration for those areas; actual evapotranspiration for areas of vegetation with medium water holding capacity was taken to be .16 times the potential. Recent work has been done on Niwot Ridge north of the basin which indicates that actual evapotranspiration rates for local alpine tundra are .16 of the potential evapotranspiration rates (Le Drew, pers. comm., 1974). For the bedrock and talus areas of the basin, evaporation rates are somewhat more difficult to calculate. Little work has been done in either measuring or calculating evapotranspiration from bare or lichen covered rock surfaces. Consequently, we assume in this study that evaporation from areas of bare rock accounts for 1 mm of water after every summer rainstorm which is followed by at least 6 hours with no rain. Where the storm total is less than 1 mm, it is assumed to be totally evaporated.

By using Table 13 and equation (11), an estimate of actual evapotranspiration can be made for the basin for each week in which temperature and precipitation records are available (Table 14).

CONCLUSION

In this study generated discharge is used as one outflow of the water budget. At the beginning of the season generated discharge is much greater than observed discharge (Table 12; Leaf, 1969b). A large portion of the generated discharge at the beginning of the season contributes to groundwater recharge rather than to observed flow. However, later in the season, negative generated discharge occurs (Table 12) which is associated with weeks of low input (Table 11). During this time, observed discharge results largely from storage flow.

Evapotranspiration is the second source of output from the water budget. However, evapotranspiration is not as important in an alpine watershed as it is in a forested watershed because of the relatively small proportion of vegetated areas in the alpine. As a result of the limited vegetation, evapotranspiration can occur over only 20.8% of the basin (Table 13). Table 15 gives a summary of the output from the water budget for the season.

TABLE 13

BASIN DIVIDED ON WATER-HOLDING CAPACITY
USED IN ESTIMATING ACTUAL EVAPOTRANSPIRATION

	Upper basin		Lower Basin		Total Basin	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Wet	13.6	7.0	19.8	18.4	33.5	11.1
Medium	24.8	12.8	4.3	4.0	29.1	9.7
Unvegetated	155.8	80.2	83.5	77.5	239.3	79.3
Total	194.2	64.3	107.7	35.7	301.9	

TABLE 14a

POTENTIAL AND ACTUAL EVAPOTRANSPIRATION
(Upper Basin)

Week Date	Number of PPT events (PE)	Potential ET (cm) (weekly totals) (PET)	Actual (cm) Wet	Actual (cm) Medium	Actual (cm) Unvegetated	Actual (cm) Total
			PET x $\frac{13.6400}{194.2460}$	PET x .16 x $\frac{24.8000}{194.2460}$	PE x $\frac{1558\ m^2}{194.2460}$ x .01	Wet + Med + Unvegetated
May 17-21	1	.72	.05	.02	.08	.15
May 22-28	3	.83	.06	.02	.24	.32
May 29-June 4	5	.71	.05	.02	.40	.47
June 5-11	0	1.11	.08	.02	.00	.10
June 12-18	6	.81	.06	.02	.48	.56
June 19-25	0	1.14	.08	.02	.00	.10
June 26-July 2	1	1.46	.10	.03	.08	.21
July 3-9	2	1.56	.11	.03	.16	.30
July 10-16	5	1.19	.08	.02	.40	.51
July 17-23	5	1.05	.07	.02	.40	.50
July 24-30	3	1.07	.08	.02	.24	.34
July 31-Aug 6	3	1.11	.08	.02	.24	.34
Aug 7-13	1	1.25	.09	.03	.08	.19
Aug 14-20	1	1.29	.09	.03	.08	.19
Aug 21-27	3	1.15	.08	.02	.24	.34
Aug 28-Sept 3	2	.82	.06	.02	.16	.24
Sept 4-10	2	.90	.06	.02	.16	.24
Sept 11-17	2	.74	.05	.02	.16	.23
Sept 18-24	0	.75	.05	.02	.00	.07
Sept 25-Oct 1	7	.48	.03	.01	.56	.60
Oct 2-8	1	.42	.03	.01	.08	.12
Oct 9-15	1	.41	.03	.01	.08	.12
Oct 16-22	0	.53	.04	.01	.00	.05
Oct 23-29	0	.37	.03	.01	.00	.03
Total	54	21.87	1.54	.45	4.33	6.31

TABLE 14b

POTENTIAL AND ACTUAL EVAPOTRANSPIRATION
(Total Basin)

Week Date	Number of PPT events (PE)	Potential ET (cm) (weekly totals) (PET)	Actual ET (cm)			
			Wet	Medium	Unvegetated	Total
			PET x 33.4800 / 301.9400	PET x .16 x 29.1400 / 301.9400	PE x 2393m^2 / 301.9400 x .01	Wet + Med + Unvegetated
May 17-21	1	.72	.08	.01	.08	.17
May 22-28	3	.83	.09	.01	.24	.34
May 29-June 4	5	.71	.08	.01	.40	.49
June 5-11	0	1.11	.12	.02	.00	.14
June 12-18	6	.81	.09	.01	.48	.58
June 19-25	0	1.14	.13	.02	.00	.14
June 26-July 2	1	1.46	.16	.02	.08	.26
July 3-9	2	1.56	.17	.02	.16	.36
July 10-16	5	1.19	.13	.02	.40	.55
July 17-23	5	1.05	.12	.02	.40	.53
July 24-30	3	1.07	.12	.02	.24	.37
July 31-Aug 6	3	1.11	.12	.02	.24	.38
Aug 7-13	1	1.25	.14	.02	.08	.24
Aug 14-20	1	1.29	.14	.02	.08	.24
Aug 21-27	3	1.15	.13	.02	.24	.38
Aug 28-Sept 3	2	.82	.09	.01	.16	.26
Sept 4-10	2	.90	.10	.01	.16	.27
Sept 11-17	2	.74	.08	.01	.16	.25
Sept 18-24	0	.75	.08	.01	.00	.09
Sept 25-Oct 1	7	.48	.05	.01	.56	.62
Oct 2-8	1	.42	.05	.01	.08	.13
Oct 9-15	1	.41	.04	.01	.08	.13
Oct 16-22	0	.53	.06	.01	.00	.07
Oct 23-29	0	.37	.04	.01	.00	.05
Total	54	21.87	2.43	.34	4.28	7.04

TABLE 15

SUMMARY OF OUTFLOW FROM WATER BUDGET
(Generated Discharge + Evapotranspiration)

Week Date	D-4 (cm)	Albion (cm)
June 13 - 19	--	-11.60
1 June 19 - 25	43.56	25.22
2 June 26 - July 2	7.74	10.14
3 July 3 - 9	11.35	6.12
4 July 10 - 16	8.64	8.35
5 July 17 - 23	- 6.17	1.83
6 July 24 - 30	7.04	4.81
7 July 31 - Aug 6	7.26	2,86
8 Aug 7 - 13	- 5.81	- 2.01
9 Aug 14 - 20	8.72	5.40
Aug 21 - 27	- 0.55	2.16
Aug 28 - Sept 3	- 6.16	0.33
Sept 4 - 10	3.72	1.37
Sept 11 - 17	- .30	1.21
Sept 18 - 24	.93	.02
Sept 25 - Oct 1	.51	.88
Oct 2 - 8	.38	--
Total	80.86	57.08

CHAPTER IV

A WATER BUDGET FOR THE GREEN LAKES VALLEY

The water budget of equation (1) is based on the continuity equation and has the form:

$$Q = P - E_t - \Delta S \tag{1}$$

where: Q = stream discharge

P = one or more precipitation terms

E_t = sum of evaporation, sublimation, and transpiration losses and gains

ΔS = change in storage

Here, equation (1) can be decomposed to the units considered already as:

$$Q_{gen} = SM + PPT - ET_w - ET_m - ET_{uv} \tag{12}$$

where: Q_{gen} = generated discharge

SM = snowmelt from winter accumulation

PPT = precipitation

ET_w = evapotranspiration from wet areas (e.g. lakes, streams, bogs, willows)

ET_m = evapotranspiration from tundra vegetation

ET_{uv} = evapotranspiration from unvegetated areas (e.g. bedrock and talus)

Generated discharge has previously been defined as simply discharge resulting from snowmelt. However, in using generated discharge to compute a water budget precipitation and evaporation must be considered. Consequently, generated discharge here includes the evaporation and precipitation terms as well as the snowmelt term. The change of storage term of equation (1) is included in the Q_{gen} term of equation (12). When a large portion of the input to a water budget is derived from snowpack depletion, it is useful to evaluate the water budget in terms of equation (12). In this study a water budget is calculated for D-4 and Albion for the weekly intervals from June 25 to August 20 which corresponds to the weekly ablation measurements taken during the season.

Input to Water Budget

The inputs to the weekly water budget consist of weekly estimates of snowmelt and precipitation. Precipitation contributions are relatively straight forward and discussed in Chapter II. However, estimates of weekly contributions due to snowmelt are more difficult to quantify. From density and snowpack lowering measurements it is possible to estimate the snow water equivalent of ablation over snow covered areas. However, it is also necessary to have an estimate of the relative proportion of snow covered area within the basin. This has been empirically derived by equation (3) of Chapter II (Table 8). Total error in the seasonal water budget of D-4 is minimized when N equals 3.5 (equation 3).

Output of the Weekly Water Budget

The major outflow from the water budget is that of generated discharge. Snowmelt and precipitation during a given period contribute to groundwater recharge and observed discharge, both of which constitute generated runoff.

Figure 9 is a summary of snow cover depletion, generated discharge and observed discharge from D-4 and Albion. It should be noted that for the entire basin 44% of the season's generated discharge was produced during the first three weeks of the season and before 67% of the watershed became bare of snow (Fig. 9b). (Flow began approximately one week earlier at Albion than at D-4.) In the upper basin 83% of the season's generated discharge was produced during the first three weeks of streamflow and before 64% of the basin had become snowfree (Fig. 9a). As a result of the difficulties described in Chapter III associated with computing generated discharge at the Albion location, it is felt that data from D-4 give a more accurate description of streamflow from an alpine basin.

Watershed Efficiency

Watershed efficiency (generated runoff expressed as a percentage of snowmelt and precipitation input) can also be computed for each of the 9 weeks during the season (Leaf, 1971). Figure 10

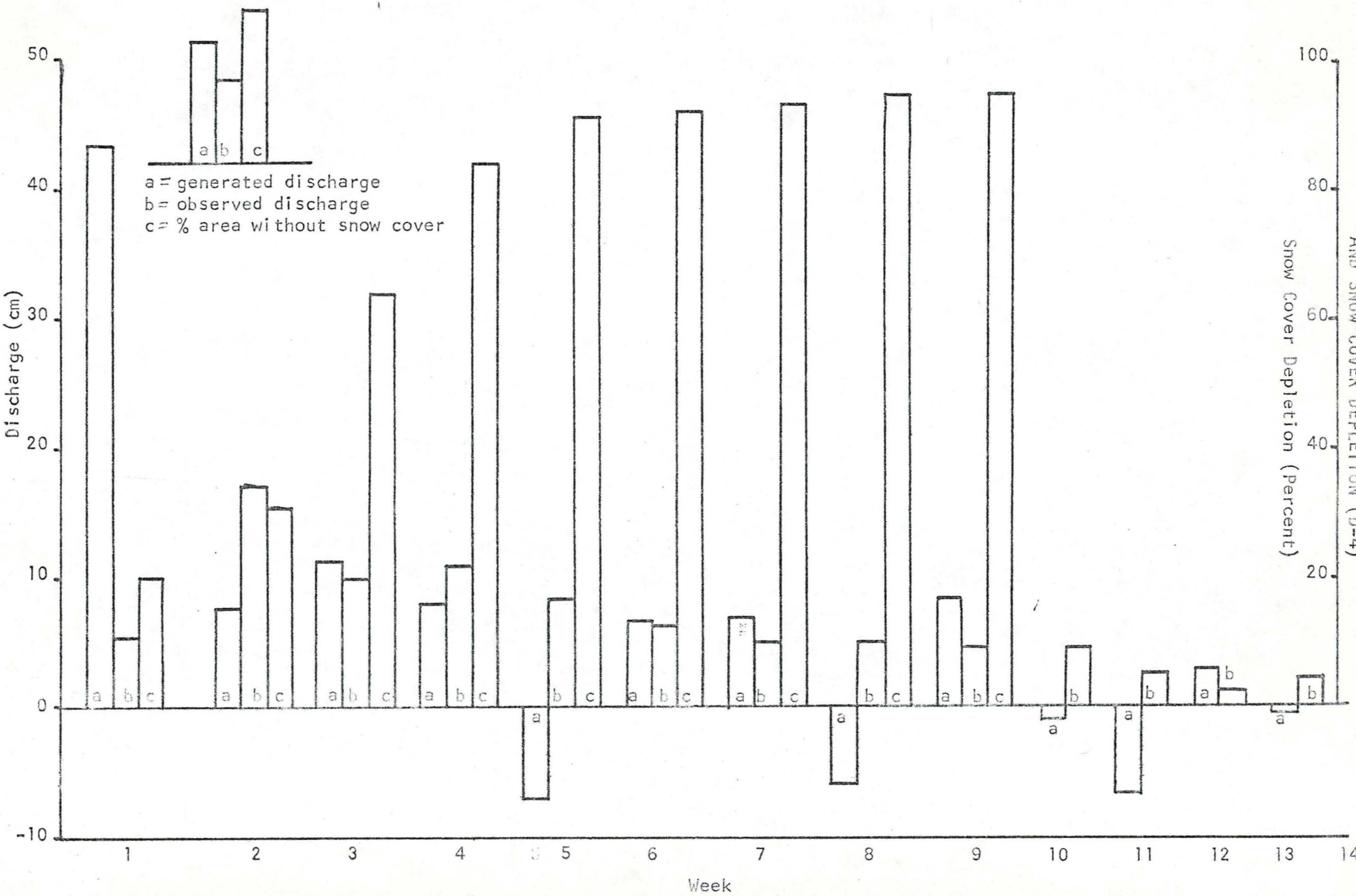


FIGURE 9a

GENERATED AND OBSERVED DISCHARGE AND SNOW COVER DEPLETION (D-4)

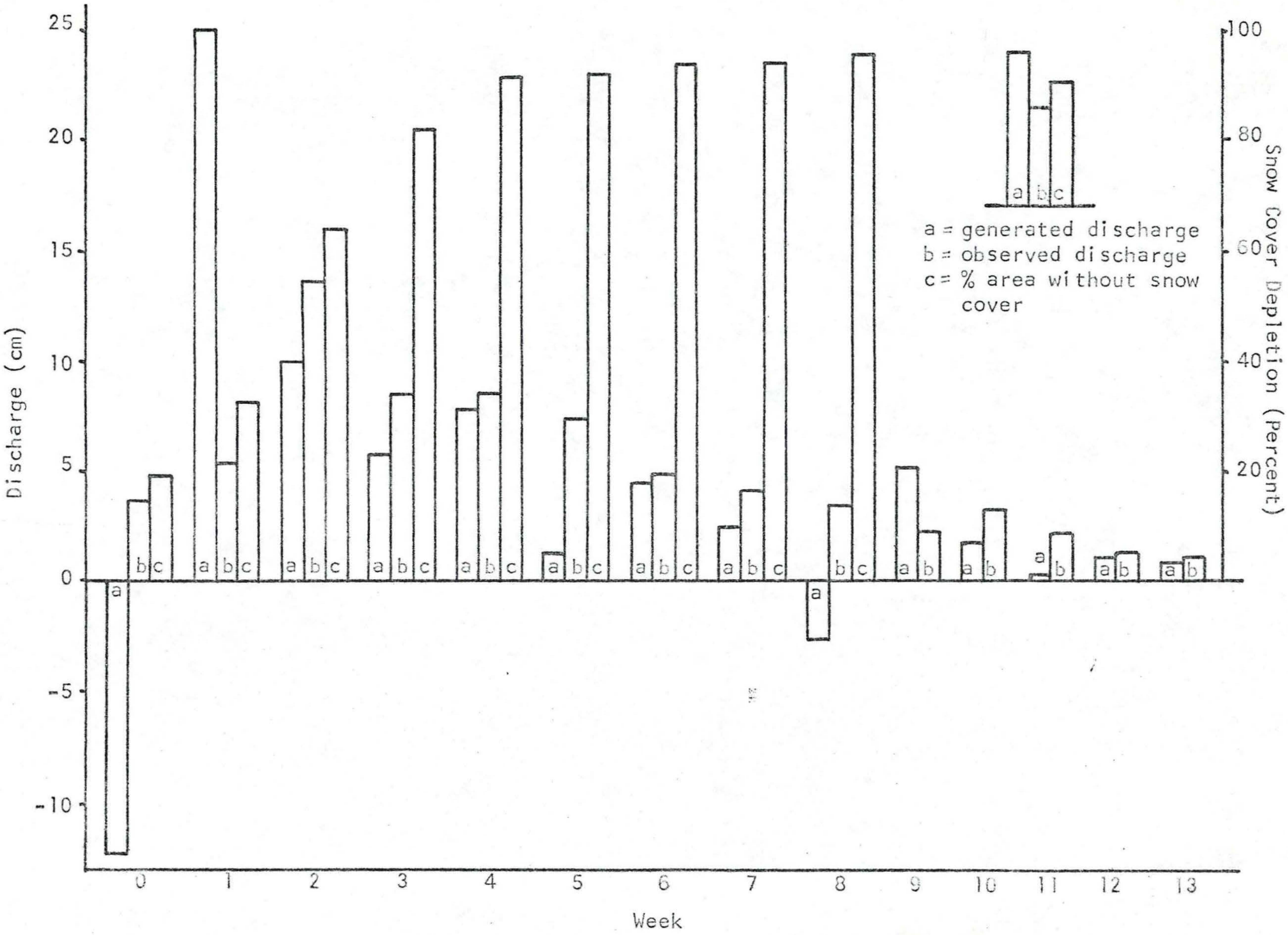
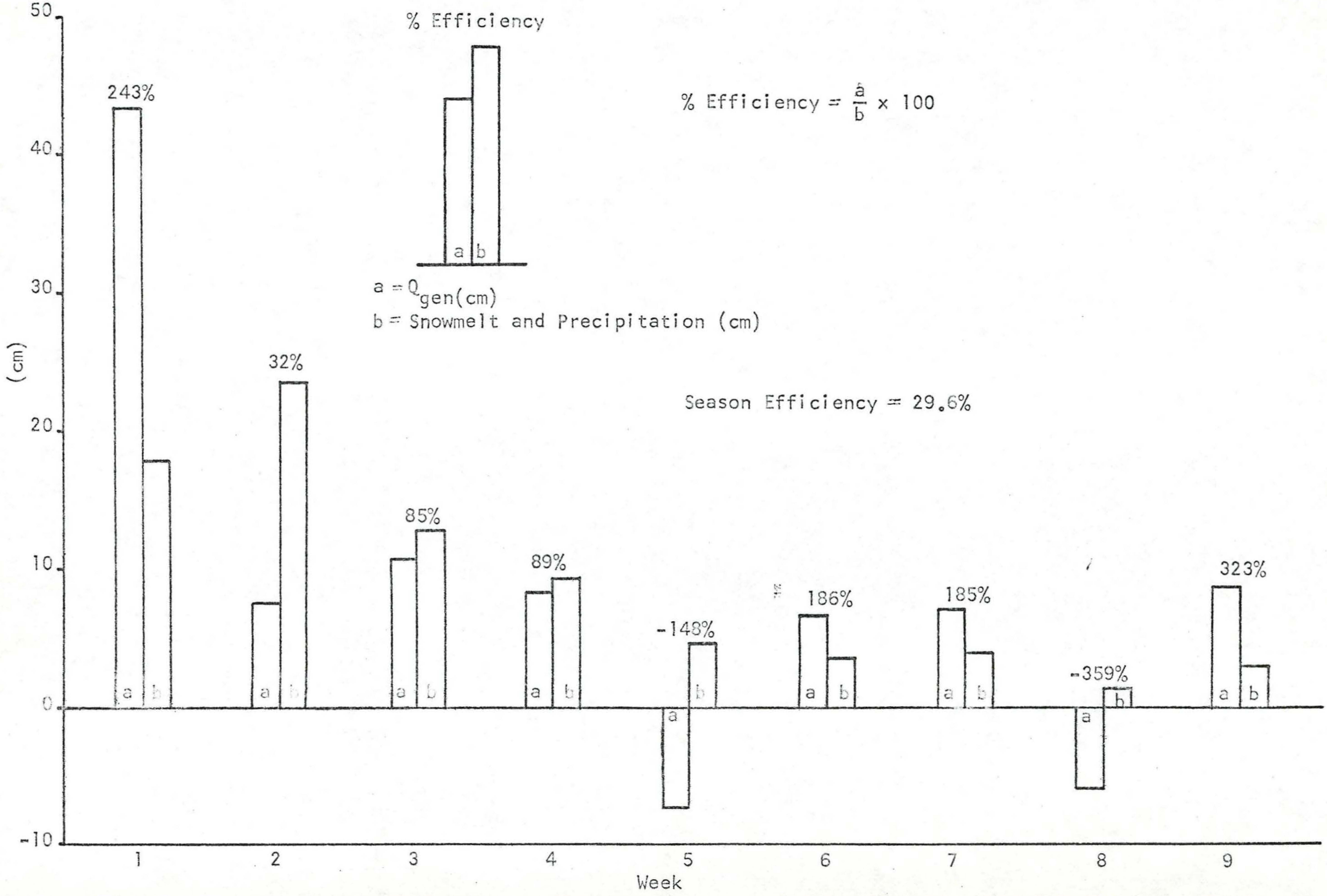


FIGURE 9b

GENERATED AND OBSERVED DISCHARGE AND SNOW COVER DEPLETION (Albion)



BASIN EFFICIENCY
D-4

FIGURE 10a

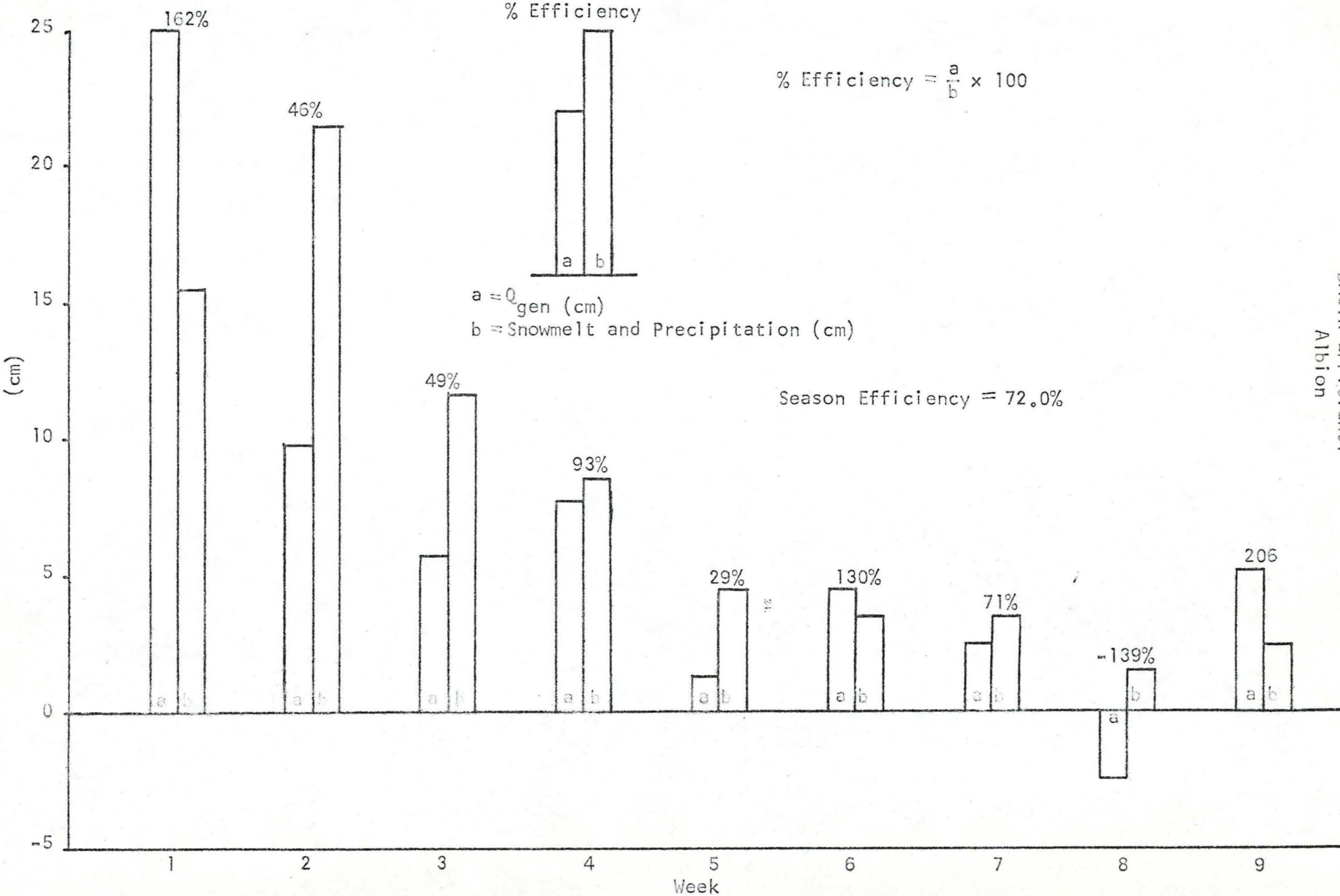


FIGURE 10b

BASIN EFFICIENCY
Albion

gives a comparison of snowmelt and precipitation with generated discharge and basin efficiency for both the D-4 and Albion location. Again, the D-4 data are probably more useful than those for the entire basin.

Water Budget

The water budgets for both the upper basin (D-4) and the total basin (Albion) are given in Table 16. The precipitation data are derived from field observation and consequently introduce relatively little error into the computations. The evapotranspiration component is computed from daily temperature field data (Hamon, 1963) and contributes relatively little to the water budget (Tables 14 and 16). Other inputs to the water budget are based on weekly ablation measurements and density measurements of the snowpack. Estimates of the area of the basin covered by snow were derived from equation (3). By the use of areal snow cover estimates and ablation measurements, an estimate was made of the weekly snowmelt input to the water budget. The rate of snowmelt input is a function of the exponent, N, in equation 3. The error term of the water budget (Table 16) is reduced to an acceptably low level for the D-4 water budget (Table 16a) of 2.67 cm when $N = 3.5$. However, the error term is much higher in the Albion water budget (Table 16b); this error is associated with the difficulties of calculating generated discharge after it has been routed through the four lakes of the basin. Because of the routing problems through the basin (Figure 1), it is felt that a better estimate of generated discharge is derived from the data of the upper basin.

CONCLUSION

The water budget of the basin was computed for the weeks which correspond to the weeks when field ablation measurements were taken in order to use a snowmelt input term in the water budget. Generated discharge was also computed for the same weekly intervals; consequently, negative values of generated discharge occur (Figure 9, Table 16). Negative generated discharge is associated with "dry" periods during the season. For example, during the fifth week negative generated

discharge occurred in the upper basin (Table 16). It was also during the fifth week that the lowest mean weekly temperature was recorded for the nine week period. Consequently, relatively little input from snowmelt was available during the fifth week causing much of the observed discharge to flow from storage. In this example, a "dry" week was detected by two independent techniques. Low input from snowmelt during a week with a low mean temperature was detected from the weekly ablation measurements. However, a "dry" week was also detected by the technique used to generate discharge in this study. There were 910891 m^3 in storage at the end of the fourth week and only 621282 m^3 in storage at the end of the fifth week. During the "dry" period 289609 m^3 flowed from storage to contribute to the 159983 m^3 observed flow for the period.

TABLE 16a

D-4 WATER-BUDGET (cm)

Week	Q_{gen}	Snow melt	PPT	Potent ET (WET)	.16×PET (Medium)	ET Unveg.	Error
1	43.46	17.88	0	.08	.02	.00	25.68
2	7.53	22.93	.62	.10	.03	.08	-15.81
3	11.05	11.69	1.24	.11	.03	.16	- 1.58
4	8.13	4.96	4.17	.08	.02	.40	- 0.50
5	- 6.67	2.00	2.51	.07	.02	.40	-10.69
6	6.70	2.17	1.44	.08	.02	.24	3.43
7	6.92	1.82	1.92	.08	.02	.24	3.52
8	- 6.00	1.53	.14	.09	.03	.08	- 7.47
9	8.53	1.56	1.08	.09	.03	.08	6.09
Total	79.65	66.54	13.12	.78	.18	1.68	2.67

TABLE 16b

ALBION WATER-BUDGET (cm)

Week	Q_{gen}	Snow melt	PPT	Potent ET (WET)	.16×PET (Medium)	ET Unveg.	Error
1	25.08	15.45	0	.13	.02	.00	9.78
2	9.88	20.84	.62	.16	.02	.08	-11.32
3	5.76	10.49	1.24	.17	.02	.16	- 5.62
4	7.80	4.23	4.17	.13	.02	.40	- 0.05
5	1.30	1.94	2.51	.12	.02	.40	- 2.61
6	4.44	1.97	1.44	.12	.02	.24	1.41
7	2.48	1.58	1.92	.12	.02	.24	- 0.64
8	- 2.25	1.48	.14	.14	.02	.08	- 3.63
9	5.16	1.42	1.08	.14	.02	.08	2.90
Total	59.64	59.40	13.12	1.23	.18	1.68	- 9.78

CHAPTER V

SUMMARY

In the 3.02 km^2 basin at peak snow accumulation (May 18) the snowpack with a mean density of 3655 kg/m^3 contained 1.8×10^6 m^3 (60.47 cm) of water equivalent while the 1.92 km^2 upper basin contained 1.3×10^6 m^3 (67.63 cm) of water equivalent. During the period from May 18 to October 31, 32.48 cm of precipitation contributed an additional 1.0×10^6 m^3 and 0.6×10^6 m^3 of water over the total and upper basins respectively.

Ablation measurements were taken at weekly intervals between June 19 and August 20 at each of the 114 sites (Fig. 1) before they became snow free. During the nine week period in which ablation measurements were taken, 66.54 cm and 59.40 cm of snow water equivalent melted from the upper and total basins respectively. The period of maximum snowmelt occurred during the period June 26 - July 2 and contributed 34.5% and 35.1% of the nine week melt to the water budget of the upper and total basins respectively. During the second week mean snowpack lowering was 9.8 cm per day with a standard deviation of 2.6 cm.

Stream discharge was observed from June 19 to October 29 at D-4 and from June 14 to October 8 at Albion. Total flow for the period of observation for the entire basin (Albion) was 2.20×10^6 m^3 or 75.8 cm with a seasonal peak daily flow of 80.9×10^3 m^3 and .705 m^3 per second. Total flow for the period of observation from D-4 was 1.80×10^6 m^3 or 94.53 cm with a seasonal peak daily flow of 58.9×10^3 m^3 and .683 m^3 per second.

Peak flow occurred on June 27 at D-4 and June 28 at Albion with 59.0×10^3 m^3 and 60.9×10^3 m^3 of flow respectively. The peak daily flow at D-4 constituted 3.3% of the total seasonal D-4 flow while the peak daily flow at Albion constituted 2.8% of the total seasonal Albion flow. At D-4, 10.4% of the season's flow occurred before the June 27 peak while 16.9% of the season's flow occurred before June 28 peak at Albion. The Albion daily flow is 47.4×10^3 m^3 on the first day of observation and six days later it drops to 10.0×10^3 m^3. This sudden drop in discharge before the seasonal peak is, no doubt, associated with temperature. The seven

days before the high discharge of 47.4 x 10^3 m^3 had a mean daily temperature of 7.2° C while the seven days before the low discharge of 10.0 x 10^3 m^3 had a mean daily temperature of -0.5° C (Table A2-1).

Precipitation, ablation, and stream discharge data were used along with estimates of evapotranspiration to construct a water budget for the upper and total basin. No elements of the water budget were figured by subtraction; consequently, an error term is given in cm of water equivalent (Table 16). Total generated discharge for the upper basin is 79.65 cm with an error of 2.67 cm or 3.4%. Total generated discharge for the entire basin is 59.64 cm while the error is -9.78 cm or -16.4%. The cause for the relatively large underestimate of the water budget in the case of the entire basin is undoubtedly associated with the difficulties in determining the generated discharge at the Albion site described in Chapter 3.

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APPENDIX I

SNOW DENSITY MEASUREMENTS

Snow density measurements were taken at 17 locations with a Federal snow sampler during the May 18 snow survey. At least one density sample was taken in each of the 14 basin stratifications (Table 2).

A Federal slotted snow sampler over-estimates the snow water equivalent of its core by 9.8% (Work, et al., 1965). Consequently, a correction factor was applied to all of the Federal snow water equivalent measurements of:

$$A = M/1.098 \qquad (1)$$

where: A = actual snow water equivalent

M = measured snow water equivalent

Snowpack depths in excess of 2 m and the development of ice lenses within the snowpack make it difficult to obtain accurate density measurements in portions of the alpine. At each site in which a density sample was taken a depth measurement was also made with a snow probe. From the probe measurement, it was determined whether or not the Federal sampler penetrated the entire depth of the snowpack. In 6 of the 17 samples the Federal sampler did not penetrate the entire snowpack.

In order to estimate the density of the lower portion of the snowpack where it was not directly sampled, two Federal snow samples were taken at each of two test sites. These samples were taken approximately 30 cm apart. One sampled the entire snowpack giving depth, density, and snow water equivalent of the total snowpack. The second sampled only the top half of the snowpack. From these the mean snow density for the bottom half of the snowpack could be calculated. It was shown to be approximately 21% more dense than the upper part of the pack. Consequently, it is possible to estimate the snow water equivalent and density for the total depth of the snowpack at the 6 locations where the Federal sampler was unable to penetrate the entire depth of the snowpack. This estimate of total snowpack density does not underestimate the density so seriously as the use of the upper portion of the snowpack by itself would.

The 17 density measurements taken on the May 18 snow survey varied from 280 kg m^{-3} to 430 kg m^{-3} with a mean of 365 kg m^{-3} and a standard deviation of 49 kg m^{-3}. The density measurements were taken between 3414 m and 3786 m, a range of 372 m, with a mean elevation of 3660.5 m and a standard deviation of 110.3 m. There is no significant relationship between density and elevation.

The variation of density with time: Snow density measurements were also taken in the basin during the season. One snow density measurement was taken on June 20 and two were taken on June 25 on Arikaree glaciar with a CRREL snowpit sampling kit (Johnson, 1973, pers comm.); the results are given in Table A1-1. On July 27, snow density measurements were taken near D-4 (Figure A1-1) again with the CRREL snowpit sampling kit (Table A1-1). A simple linear regression of density on time gives a relationship of:

$$DEN = .35975 + .00359 \times DAY \qquad (2)$$

where: DEN = snow density, and

DAY = number of days after May 17

The R value of equation (2) is .996 and is significant at the .0005 level while the standard error of the estimate is .009 (Figure A1-2). From equation (2) a mean snow density for the basin was derived for each week in which ablation measurements were taken (Table A1-2). After July 27 the basin snowpack is assumed constant at 625 kg m^{-3}.

These density data are used with basin snow cover and snowpack lowering measurements in order to estimate weekly ablation.

SNOWPACK LOWERING MEASUREMENTS

It is necessary to have some estimate of snowpack lowering in order to determine ablation rates. These measurements are commonly made with ablation stakes; the amount of snowpack lowering is the difference between the levels of the snow surface measured with the ablation stake at two different times. Error can occur if the ablation stake sinks within the snowpack due to differential melt around the ablation stake. To test for ablation stake lowering within the snowpack

as a result of melt, four test sites were established (Fig. A1-1). At each site, two stakes were placed in the snowpack approximately 5 m apart. One stake was placed where the snowpack was less than 1.5 m deep (the length of each ablation stake); consequently, it rested on the ground. The other stake was placed nearby where the depth of the snowpack was greater than 2.5 m. The stakes at the test sites were measured at weekly intervals from June 25 to July 31 giving a total of 13 paired observations from a possible 20 (melt-out at two or more sites occurred during the last 3 of the 5 weeks). If significant differential lowering of ablation stakes due to melt within the snowpack does not occur, the mean snowpack lowering measured by stakes which rest on the ground would not be significantly different from the mean snowpack lowering measured by stakes which do not rest on the ground. A T-test was used to test H_o:

$$\mu_1 - \mu_2 = 0 \qquad (3)$$

where: μ_1 = the mean snowpack lowering measured by stakes resting on the ground

μ_2 = the mean snowpack lowering measured by stakes not resting on the ground

The null hypothesis cannot be rejected at the .05 level. Other workers have obtained similar results (Johnson, pers. comm., 1973).

FIGURE A1-2

VARIATION OF DENSITY WITH TIME

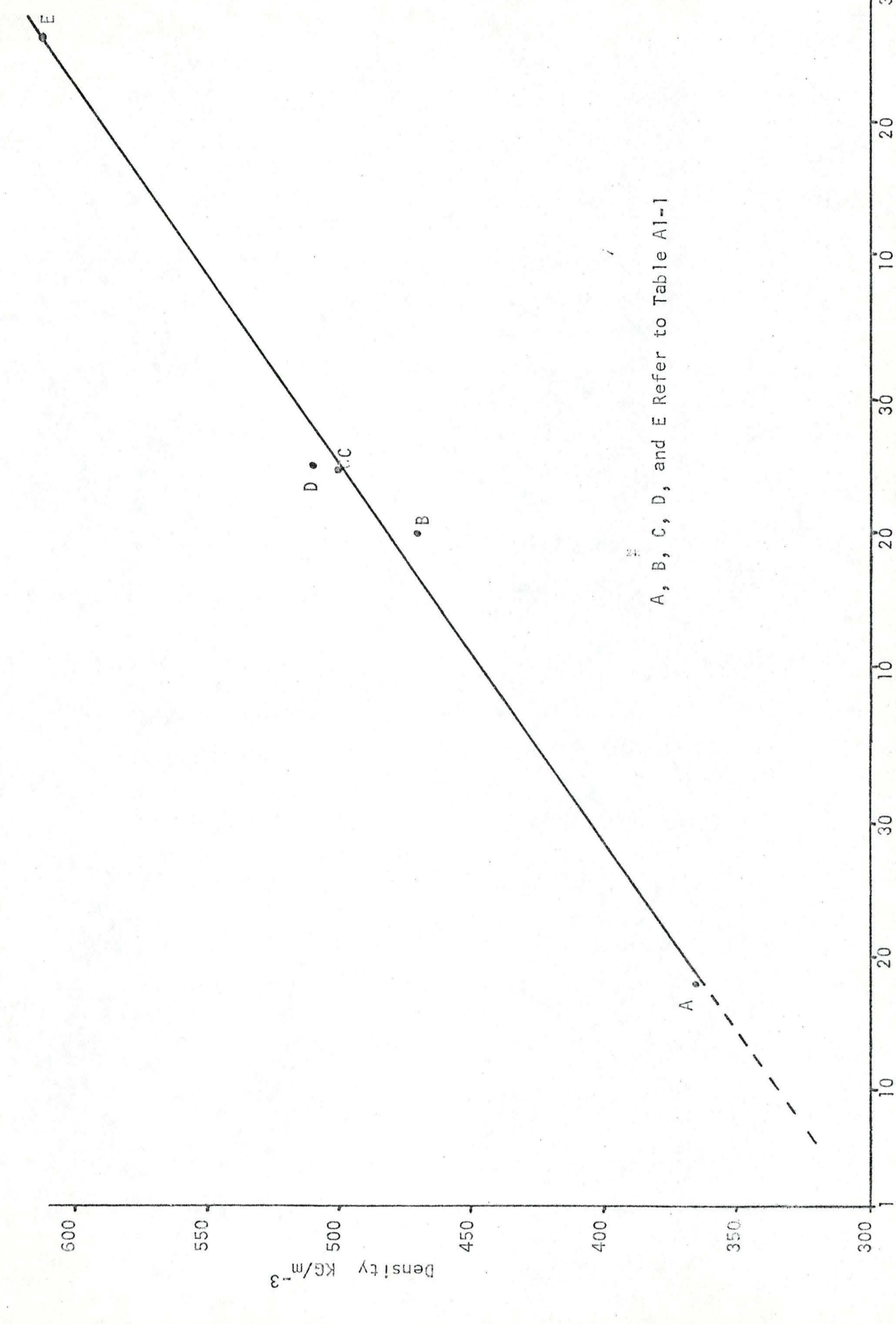


TABLE A1-1

SNOW DENSITY MEASUREMENTS
(kg/m^3)

A May 18 Snow Survey-TC $\overline{X}_{den}$ = 36.5	B June 20 Arikaree-JJ		C June 25 Arikaree-JJ		D June 25 Arikaree-JJ		E July 27 D-4 - TC	
	Depth (cm)	Density	Depth (cm)	Density	Depth (cm)	Density	Depth (cm)	Density
	0-19	320	0-50	560	0-50	510	0-20	580
	19-38	360	50-100	510	50-100	510	20-40	570
	38-57	430	100-150	520	100-150	510	40-60	590
	57-76	480	150-200	620	150-200	530	60-80	620
	76-95	480	200-250	490	200-250	500	80-100	630
	95-114	560	250-300	500	250-300	490	100-120	630
	114-133	520	300-350	490	300-350	500	120-140	640
	133-152	520	350-400	460	350-400	460	240-160	640
	152-171	520	400-450	450	400-450	470	160-180	620
	171-190	520					180-194	630
	$\overline{X}$ = 471		$\overline{X}$ = 511		$\overline{X}$ = 498		$\overline{X}$ = 615	

JJ = Jim Johnson

TC = Tom Carroll

TABLE A1-2

SNOW DENSITIES USED FOR WEEKLY ABLATION MEASUREMENTS

Week	Dates	Density (kg/m^3)
1	June 19 - June 25	489
2	June 26 - July 2	514
3	July 3 - July 9	539
4	July 10 - July 16	564
5	July 17 - July 23	590
6	July 24 - July 30	615
7	July 31 - Aug 6	615
8	Aug 7 - Aug 13	615
9	Aug 15 - Aug 20	615

TABLE A1-3

WEEKLY SNOW WATER EQUIVALENT ABLATION ($m^3 \times 10^3$)
AND PERCENT OF NINE WEEK TOTAL ABLATION
(Upper Basin)

ELEVATION

Week	1		2		3		4		Total	
1	40.1	2.9	79.7	5.7	119.7	8.6	117.4	8.5	356.9	25.7
2	51.8	3.7	107.0	7.7	148.7	10.7	165.0	11.9	472.5	34.1
3	20.7	1.5	57.4	4.1	79.0	5.7	92.1	6.6	249.2	18.1
4	13.1	0.9	20.4	1.5	26.4	1.9	38.7	2.8	98.6	7.1
5	5.5	0.4	9.2	0.7	15.8	1.1	10.9	0.8	41.5	3.0
6	4.6	0.3	13.2	1.0	16.6	1.2	12.5	0.9	46.9	3.4
7	5.0	0.4	10.8	0.8	11.8	0.9	12.3	0.9	39.9	2.9
8	4.5	0.3	9.8	0.7	13.1	0.9	12.4	0.9	39.6	2.9
9	3.7	0.3	12.4	0.9	12.6	0.9	12.4	0.9	41.1	3.0
Total	149.0	10.7	319.9	23.1	443.7	32.0	473.7	34.2	1386.4	

SLOPE

Week	Steep		Medium		Flat		Total	
1	282.7	20.0	46.8	3.3	57.4	4.1	387.0	27.4
2	358.8	25.4	61.3	4.3	66.6	4.7	486.7	34.4
3	182.6	12.9	32.8	2.3	27.7	2.0	243.2	17.2
4	64.2	4.5	14.6	1.6	22.2	1.6	101.0	7.1
5	28.8	2.0	6.3	0.4	4.9	0.3	40.0	2.8
6	35.0	2.5	5.6	0.4	5.9	0.4	46.5	3.3
7	28.1	2.0	5.5	0.4	8.4	0.6	42.0	3.0
8	29.4	2.1	4.7	0.3	0.4	0.0	34.5	2.4
9	27.9	2.0	4.1	0.3	0.5	0.0	32.5	2.3
Total	1057.5	73.4	181.8	12.9	194.1	13.7	1413.3	

TABLE A1-3 (cont.)

ASPECT

Week	Flat		North		South		East		Total	
1	64.9	5.7	60.1	5.2	118.7	10.3	61.8	5.4	305.6	26.6
2	74.3	6.5	79.9	7.0	170.9	14.9	70.9	6.2	396.1	34.5
3	31.8	2.8	51.7	4.5	83.7	7.3	36.7	3.2	203.8	17.8
4	23.6	2.1	14.4	1.3	30.1	2.6	13.5	1.2	81.6	7.1
5	5.0	0.4	9.2	0.8	13.1	1.1	6.1	0.5	33.4	2.9
6	6.2	0.5	9.4	0.8	15.5	1.4	7.0	0.6	38.1	3.3
7	8.7	0.8	6.6	0.6	13.8	1.2	5.7	0.5	34.8	3.0
8	0.5	0.0	6.6	0.6	13.2	1.2	6.2	0.5	26.6	2.3
9	0.6	0.1	9.2	0.8	12.6	1.1	5.4	0.5	27.8	2.4
Total	215.7	18.8	247.0	21.5	471.6	41.1	213.5	18.6	1147.8	

DEPTH

Week	Deep		Medium		Light		Total	
1	54.5	4.1	192.5	14.6	102.3	7.8	349.3	26.5
2	73.3	5.6	250.8	19.1	129.1	9.8	435.2	34.4
3	39.0	3.0	133.0	10.1	62.2	4.7	234.2	26.5
4	13.4	1.0	45.0	3.4	48.0	3.6	106.4	8.1
5	5.7	0.4	21.8	1.7	15.8	1.2	43.3	3.3
6	7.3	0.6	25.1	1.9	9.3	0.7	41.7	3.2
7	5.9	0.4	20.0	1.5	3.2	0.2	29.2	2.2
8	6.4	0.5	20.6	1.6	0.9	0.1	28.0	2.1
9	6.3	0.5	24.4	1.9	0.0	0.0	30.7	2.3
Total	211.8	16.1	733.2	55.7	370.8	28.2	1315.9	

TABLE A1-4

WEEKLY SNOW WATER EQUIVALENT ABLATION ($m^3 \times 10^3$)

AND PERCENT OF NINE WEEK TOTAL ABLATION

(Total Basin)

ELEVATION

Week	1		2		3		4		Total	
1	108.6	5.7	106.1	5.5	143.9	7.5	120.5	6.3	479.1	24.9
2	179.1	9.3	142.5	7.4	183.3	9.5	165.9	8.6	670.8	34.9
3	82.0	4.3	76.4	4.0	93.4	4.9	92.5	4.8	344.2	17.9
4	32.0	1.7	27.2	1.4	31.6	1.6	39.6	2.1	130.4	6.8
5	18.7	1.0	12.3	0.6	19.1	1.0	11.0	0.6	61.1	3.2
6	14.4	0.8	17.6	0.9	20.0	1.0	12.6	0.7	64.6	3.4
7	13.2	0.7	14.3	0.7	14.2	0.7	12.4	0.6	54.1	2.8
8	18.7	1.0	13.0	0.7	15.7	0.8	12.5	0.6	59.8	3.1
9	14.3	0.7	16.5	0.9	15.2	0.8	12.5	0.7	58.5	3.0
Total	481.0	25.0	425.8	22.1	536.3	27.9	479.5	24.9	1922.6	

SLOPE

Week	Steep		Medium		Flat		Total	
1	362.7	18.6	83.1	4.3	66.1	3.4	511.9	26.3
2	488.3	25.1	120.1	6.2	74.8	3.8	683.2	35.1
3	245.6	12.6	63.0	3.2	31.8	1.6	340.4	17.5
4	85.2	4.4	22.8	1.2	22.9	1.2	130.9	6.7
5	41.4	2.1	13.5	0.7	5.0	0.3	59.9	3.1
6	47.8	2.5	10.3	0.5	6.1	0.3	64.2	3.3
7	37.0	1.9	10.5	0.5	8.7	0.4	56.1	2.9
8	49.2	2.3	8.9	0.5	0.4	0.0	53.6	2.7
9	40.7	2.1	7.6	0.4	0.5	0.0	48.8	2.5
Total	1393.0	71.5	339.6	17.4	216.3	11.1	1948.9	

TABLE A1-4 (cont.)

ASPECT

Week	Flat		North		South		East		Total	
1	69.0	4.0	106.8	6.2	165.7	9.6	102.3	6.0	443.9	25.8
2	78.1	4.5	152.1	8.9	238.2	13.9	132.3	7.7	600.7	35.0
3	33.6	2.0	89.2	5.2	118.9	6.9	64.6	3.8	306.3	17.8
4	23.9	1.4	25.6	1.5	44.0	2.6	23.9	1.4	117.3	6.8
5	5.1	0.3	16.7	1.0	19.5	1.1	12.4	0.7	53.7	3.1
6	6.2	0.4	16.2	0.9	22.0	1.3	12.4	0.7	56.8	3.3
7	8.8	0.5	12.7	0.7	19.3	1.1	8.4	0.5	49.2	2.9
8	0.5	0.0	15.2	0.9	18.5	1.1	11.9	0.7	46.2	2.7
9	0.6	0.0	15.5	0.9	7.0	1.0	11.2	0.7	44.4	2.6
Total	225.8	13.1	450.0	26.2	663.2	38.6	379.6	22.1	1718.6	

DEPTH

Week	Deep		Medium		Light		Total	
1	55.6	3.2	232.1	13.5	156.2	9.1	443.9	25.9
2	76.5	4.5	330.0	19.2	196.9	11.5	603.4	35.2
3	39.1	2.3	171.5	10.0	93.2	5.4	303.9	17.7
4	13.7	0.8	56.1	3.3	65.4	3.8	135.2	7.9
5	6.0	0.3	30.8	1.8	25.6	1.5	62.3	3.6
6	7.4	0.4	30.2	1.8	19.9	1.2	57.5	3.4
7	6.0	0.4	25.8	1.5	6.5	0.4	38.3	2.2
8	6.7	0.4	26.0	1.5	1.9	0.1	34.6	2.0
9	6.8	0.4	28.9	1.7	0.0	0.0	35.7	2.1
Total	217.9	12.7	931.4	54.3	565.5	33.0	1714.8	

APPENDIX II

Table A2-1 gives the 1973 data for D-4 and Albion discharge, precipitation, and temperature.

A rating curve was established in place at Albion with the use of a velocity head rod (Leaf, 1971) and at D-4 with a standard Price current meter. Forty observations were taken at the inlet of the Parshall flume at Albion; sixteen observations were taken at D-4. A current meter was not used at Albion because it was felt that a velocity head rod gave a better estimate of velocity of flows less than 7 cm. The rating curve for Albion and D-4 is given in Figure A2-1. Also plotted in Figure A2-1a is the theoretical rating curve for a four foot Parshall flume. The Albion rating curve estimates a greater discharge for a given stage than does the theoretical curve. This is probably due to the location of the Parshall flume. The flume was originally designed to be used in low velocity situations. However, the channel 3 m upstream from the flume is approximately 20° and consequently the flow through the flume is at a higher velocity than what the flume was designed for.

A least squares fit was used to determine the rating equation. Equations (1) and (2) are the D-4 and Albion rating equation respectively:

$$Q = .03910 \times S^{4.84419} \tag{1}$$

$$Q = 19.05214 \times S^{1.42260} \tag{2}$$

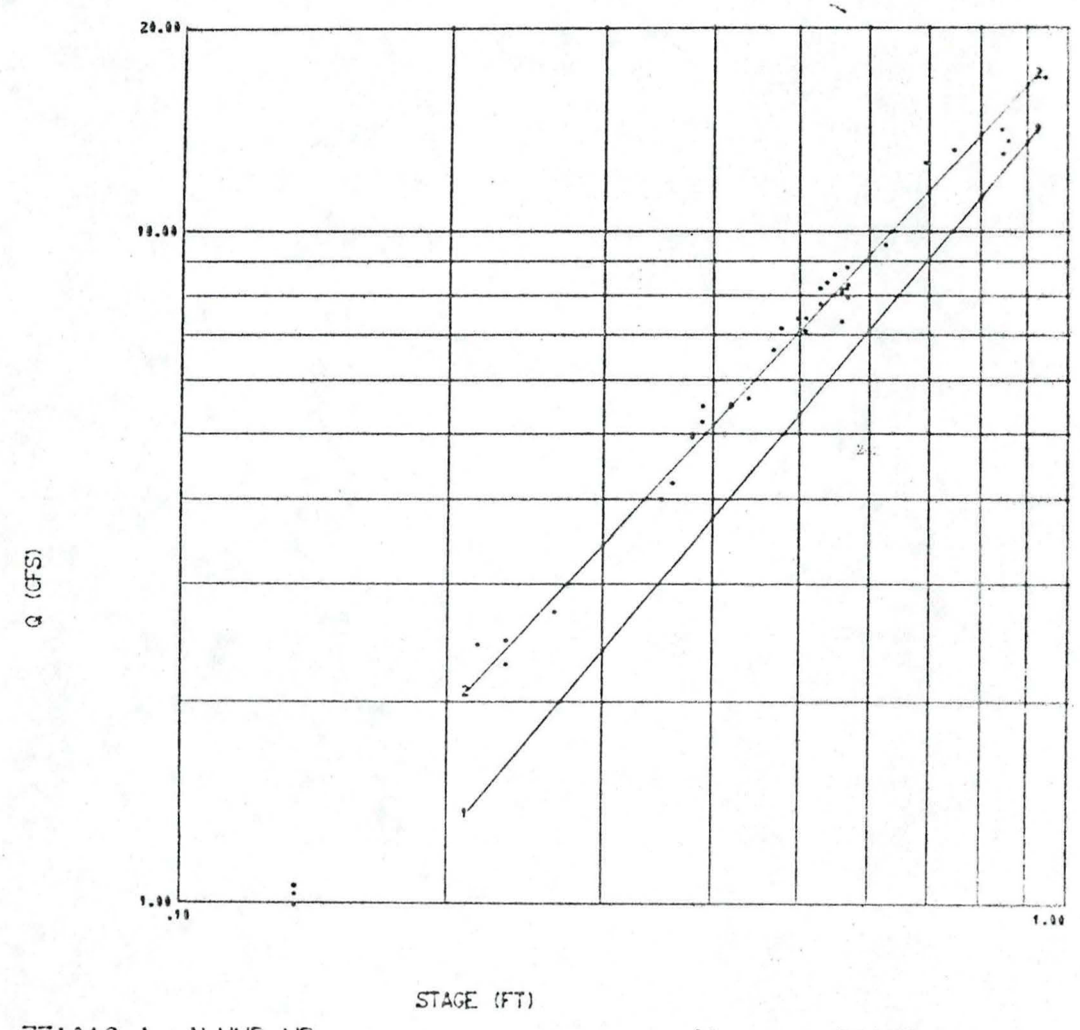
where: Q = discharge in CFS

S = stage in feet

Table A2-2 gives the data used to develop equations (1) and (2).

FIGURE A2-1a

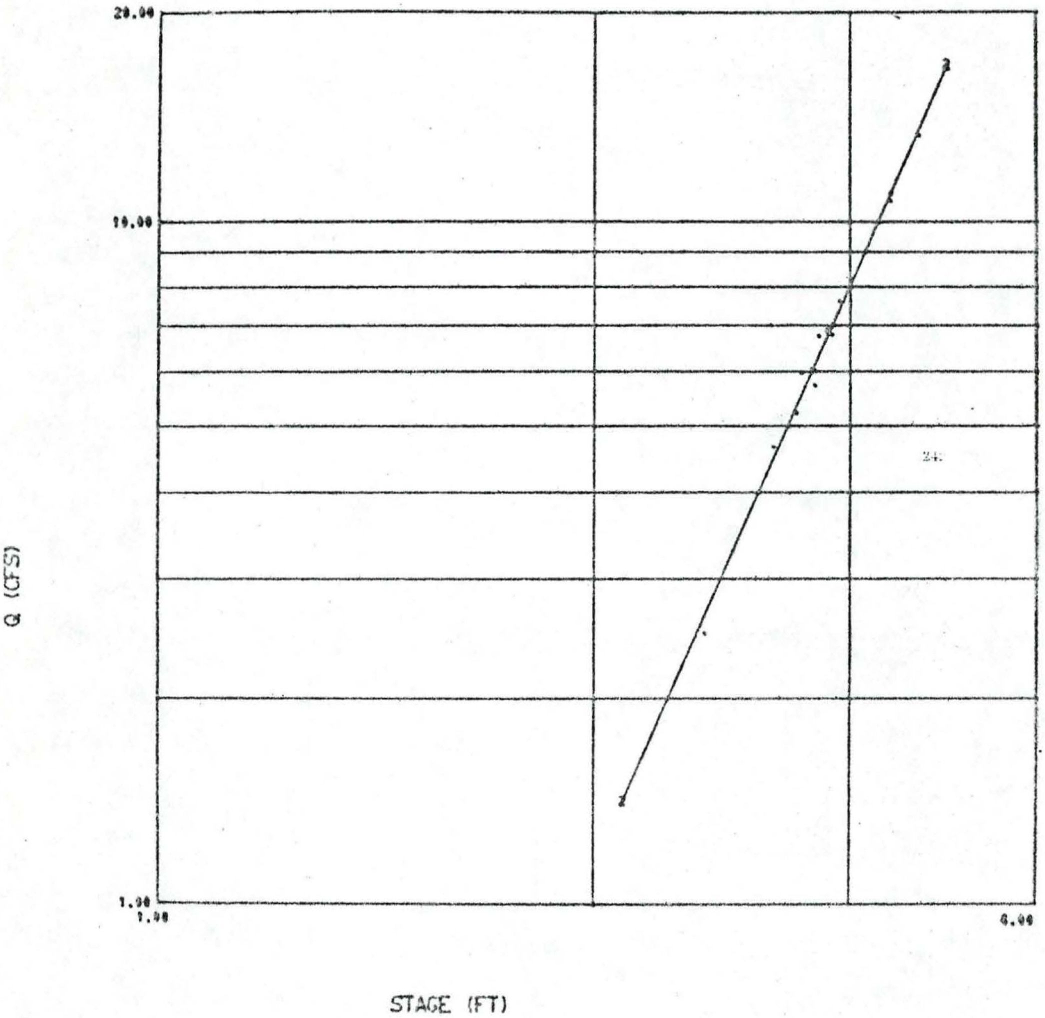
ALBION RATING CURVE



731016 A ALVHR UP 40 POINTS

FIGURE A2-1b

D-4 RATING CURVE



750916 A D-4 CM 16 POINTS

TABLE A2-1

1973 DAILY D-4 AND ALBION
OBSERVED DISCHARGE ($m^3 \times 10^3$),
PRECIPITATION (cm), AND MEAN TEMPERATURE (^oC)

Date	D-4 Discharge	Albion Discharge	Precipitation	Temperature
May 17				6.7
18				6.7
19			0.1	5.8
20			0.7	3.1
21			0.0	4.3
22			0.0	1.9
23			0.3	1.4
24			0.1	2.5
25			0.0	1.4
26			0.9	2.1
27			0.2	6.8
28			0.1	-0.8
29			0.5	-1.9
30			3.4	-1.4
31			0.0	4.2
June 1			0.0	5.6
2			0.1	-1.9
3			0.2	-3.0
4			1.5	-4.9
5			0.0	-2.1
6			0.0	2.5
7			0.0	6.5
8			0.0	5.3
9			0.0	11.2
10			0.0	10.3
11			0.0	7.9
12			0.0	6.9
13			0.8	6.7

TABLE A2-1 (cont.)

Date	D-4 Discharge	Albion Discharge	Precipitation	Temperature
June 14			0.6	2.0
15		47.4	0.5	-1.3
16		26.5	0.1	-2.4
17		17.1	0.3	2.4
18		18.5	0.3	-6.3
19	9.5	11.4	0.0	-1.0
20	7.5	10.0	0.0	2.8
21	8.1	11.6	0.0	6.6
22	16.2	17.1	0.0	7.4
23	31.7	24.4	0.0	9.7
24	33.8	26.7	0.0	9.3
25	31.8	43.3	0.0	10.1
26	49.5	52.6	0.0	10.2
27	59.0	59.5	0.0	11.3
28	55.0	60.9	0.6	9.6
29	51.6	59.1	0.0	10.3
30	42.2	55.9	0.0	10.7
July 1	38.4	52.9	0.0	11.7
2	35.2	48.8	0.0	10.6
3	28.9	44.1	0.0	12.1
4	25.4	38.6	0.0	12.1
5	25.2	38.0	0.0	13.6
6	26.4	38.9	0.0	15.0
7	26.0	39.6	0.3	10.4
8	27.3	40.3	1.0	8.9
9	33.0	43.4	0.0	9.6
10	30.1	36.9	0.0	10.1
11	28.8	34.7	0.0	12.6
12	28.9	33.6	1.2	10.8
13	36.4	42.1	1.0	4.0
14	34.3	42.5	0.7	2.4

TABLE A2-1 (cont.)

Date	D-4 Discharge	Albion Discharge	Precipitation	Temperature
July 15	25.7	33.8	0.7	4.7
16	27.2	35.1	0.6	6.0
17	26.7	35.9	0.0	8.7
18	23.1	31.8	0.5	6.5
19	27.3	34.1	0.8	6.1
20	28.8	37.8	0.5	4.4
21	24.4	33.4	0.2	4.7
22	19.7	26.4	0.3	5.9
23	17.7	24.8	0.1	5.1
24	16.4	24.3	0.0	5.9
25	15.5	22.9	0.0	4.5
26	14.5	21.0	0.0	7.4
27	15.2	21.2	0.0	7.5
28	15.4	20.6	0.5	6.9
29	16.4	22.6	0.6	7.3
30	18.4	20.9	0.3	5.0
31	16.9	21.1	0.0	6.5
August				
1	15.1	20.1	0.4	6.4
2	15.2	20.6	0.8	7.9
3	14.7	20.1	0.1	8.2
4	13.7	16.9	0.0	8.6
5	14.3	19.0	0.7	5.3
6	17.4	18.1	0.0	6.6
7	17.4	19.8	0.1	7.5
8	16.6	19.7	0.0	8.5
9	15.4	17.8	0.0	10.0
10	14.0	15.6	0.0	10.9
11	13.0	13.4	0.0	8.6
12	12.1	11.9	0.0	10.4
13	11.6	8.8	0.0	9.8

TABLE A2-1 (cont.)

Date	D-4 Discharge	Albion Discharge	Precipitation	Temperature
August				
14	11.1	6.8	0.0	10.5
15	10.9	7.0	0.0	10.4
16	10.6	6.1	0.0	12.2
17	11.5	7.4	1.0	9.5
18	15.4	10.3	0.1	8.3
19	14.8	10.5	0.0	10.9
20	13.9	13.8	0.0	10.7
21	13.7	18.3	1.3	8.5
22	13.9	17.1	0.4	6.3
23	13.7	13.9	0.0	10.1
24	13.0	14.0	0.0	9.2
25	12.4	12.5	0.0	9.9
26	11.6	11.7	0.4	8.9
27	11.1	11.8	0.0	10.4
28	10.2	10.3	0.1	7.8
29	9.6	10.0	0.0	7.2
30	8.7	9.2	0.0	6.3
31	7.6	9.0	0.0	4.2
September				
1	6.9	7.5	0.0	4.3
2	6.6	9.7	0.2	-3.2
3	6.2	10.1	0.0	0.5
4	5.7	5.2	0.0	3.7
5	5.5	5.3	0.0	6.6
6	5.4	6.3	0.0	8.1
7	5.5	6.3	0.0	8.0
8	5.8	6.4	0.0	7.7
9	5.9	5.5	0.5	4.1
10	6.2	4.6	0.5	5.7
11	6.5	5.2	0.3	1.9

TABLE A2-1 (cont.)

Date	D-4 Discharge	Albion Discharge	Precipitation	Temperature
September				
12	6.7	6.6	0.4	1.9
13	6.7	4.3	0.0	4.9
14	6.6	4.4	0.0	7.0
15	6.3	4.5	0.0	5.5
16	6.0	4.4	0.0	2.3
17	5.6	4.2	0.0	4.1
18	5.1	4.0	0.0	6.4
19	4.7	3.8	0.0	6.3
20	4.5	3.5	0.0	8.0
21	4.2	3.0	0.0	4.0
22	4.1	2.8	0.0	6.2
23	4.0	2.6	0.0	3.6
24	4.0	2.5	0.0	-2.5
25	3.9	2.6	1.4	-2.1
26	3.9	2.6	0.4	-4.3
27	3.7	2.6	0.4	-3.0
28	3.5	2.7	0.4	-3.1
29	2.9	2.7	0.4	-0.6
30	2.7	2.7	0.4	3.6
October				
1	3.0	2.4	0.4	2.5
2	3.3	2.2	0.0	-2.2
3	3.2	2.0	0.1	-2.2
4	3.2	2.0	0.0	-2.2
5	3.1	2.0	0.0	-2.2
6	3.0	2.2	0.0	-2.2
7	2.9	2.0	0.0	-2.2
8	2.9		0.0	-0.8
9	3.0		0.4	-3.2
10	3.0		0.1	-7.8

TABLE A2-1 (cont.)

Date	D-4 Discharge	Albion Discharge	Precipitation	Temperature
October				
11	2.9		0.0	-8.4
12	2.8		0.0	-6.8
13	2.7		0.0	0.5
14	2.6		0.0	4.8
15	2.6		0.0	4.4
16	2.6		0.0	3.7
17	2.5		0.0	3.5
18	2.4		0.0	2.4
19	2.5		0.0	2.4
20	2.4		0.0	2.4
21	2.4		0.0	3.5
22	2.3		0.0	4.6
23	2.3		0.0	4.3
24	2.2		0.0	-6.9
25	2.1		0.0	-1.8
26	2.1		0.0	-4.7
27	2.1		0.0	-5.9
28	2.0		0.0	0.5
29	2.0		0.0	-1.6
30			0.0	-7.7
31			0.0	

TABLE A2-1 (cont.)

D-4 Observed Discharge Summary ($m^3 \times 10^3$)					
	June	July	August	September	October
Total Discharge	395.8	772.5	404.7	155.2	76.2
cm	20.73	40.46	21.20	8.13	3.99
Flow					
Maximum	58.9	38.4	17.4	6.8	3.3
Minimum	0.0	14.5	7.6	2.7	0.0

Total Seasonal Discharge	1804.5 $m^3 \times 10^3$
	94.53 cm
Seasonal Peak Daily Flow	59.0 $m^3 \times 10^3$
	.68266 m^3/sec

Albion Observed Discharge Summary ($m^3 \times 10^3$)					
	June	July	August	September	October
Total Discharge	541.9	1042.0	421.6	138.8	58.3
cm	18.62	35.81	14.49	4.77	2.00
Flow					
Maximum	60.9	52.9	20.6	10.1	2.4
Minimum	0.0	20.6	6.1	2.5	0.0

Total Seasonal Discharge	2202.6 $m^3 \times 10^3$
	75.8 cm
Seasonal Peak Daily Flow	60.9 $m^3 \times 10^3$
	.70527 m^3/sec

TABLE A2-2

ESTIMATES OF STAGE (m) AND VOLUME DISCHARGE ($m^3 sec^{-1}$) USED TO ESTABLISH THE D-4 AND ALBION RATING CURVES

Albion		D-4	
Volume	Stage	Volume	Stage
.360	.213	.306	.979
.273	.192	.382	1.024
.405	.259	.315	.979
.483	.290	.286	.959
.388	.262	.195	.874
.371	.259	.165	.869
.376	.229	.175	.864
.246	.168	.220	.903
.238	.174	.198	.885
.223	.162	.199	.885
.213	.155	.195	.892
.227	.174	.173	.869
.235	.171	.172	.851
.210	.171	.151	.844
.236	.174	.134	.814
.206	.146	.072	.730
.241	.165		
.204	.155		
.236	.162		
.232	.171		
.254	.174		
.213	.152		
.191	.143		
.150	.119		
.142	.116		
.143	.116		
.162	.134		
.159	.128		

TABLE A2-2 (cont.)

Albion		D-4	
Volume	Stage	Volume	Stage
.158	.119		
.157	.128		
.121	.110		
.070	.066		
.065	.071		
.071	.071		
.078	.081		
.030	.041		
.030	.041		
.028	.041		

APPENDIX III

TABLE A3-1

SUMMARY OF 1974 D-4 AND ALBION DISCHARGE ($m^3 \times 10^3$) AND MEAN DAILY TEMPERATURE (^oC).

Date	D-4	Albion	Temperature
June 19		45.8	10.4
20		45.5	11.5
21		46.0	10.2
22		45.2	7.6
23		45.1	8.7
24	35.2	47.4	8.1
25	34.4	48.1	10.2
26	32.3	43.9	10.0
27	34.4	41.0	10.3
28	34.4	41.0	11.1
29	28.8	41.0	10.6
30	27.2	41.0	9.3
July 1	25.0	36.4	9.1
2	23.5	35.7	9.9
3	21.7	28.9	6.5
4	19.3	26.0	9.5
5	17.8	26.0	10.7
6	17.8	26.0	8.7
7	17.9	26.0	7.1
8	18.3	25.9	7.0
9	19.3	28.1	9.2
10	20.3	29.3	8.7
11		28.2	10.5
12		27.6	8.1
13		31.5	9.4
14		32.2	6.9
15		38.6	6.2
16		43.6	7.5

APPENDIX III

TABLE A3-1 (cont.)

Date	D-4	Albion	Temperature
July 17		36.7	8.0
18		32.0	8.1
19		37.8	9.5
20		35.4	8.6
21		35.4	6.8
22		35.4	6.1
23		35.4	8.0
24		31.9	7.2
25		28.9	9.6
26		26.6	10.5
27		22.9	9.7
28		21.2	7.8
29		19.3	5.0
30		15.9	7.8
31		14.6	8.1
August			
1		13.6	6.1
2		13.6	4.3
3		13.2	4.5
4		12.8	6.2
5		12.6	5.3
6		11.9	6.9

Appendix 4. Simulation of Green Lakes snowmelt for 1973 and for ± 50 % changes in initial snowpack.

The effects of variations in winter snow accumulation in the Green Lakes valley have been studied by means of a snowmelt model which operates on a set of grid points over a given topography. This model was described at the 1974 Western Snow Conference (Williams, 1974). For the present study, a grid was superimposed on the topographic map of the basin above the Lake Albion inlet, with grid spacing 100 m (325 ft), and elevations read at each grid point. From the elevations E_{ij}, slope and aspect at each grid point were computed according to formulas given by Sharpnack and Akin (1969). A measure R_{ij} of convexity or concavity of the surface at each grid point was defined by

$$R_{ij} = E_{i+1,j} + E_{i-1,j} + E_{i,j+1} + E_{i,j-1} - 4E_{ij}.$$

Representative values of snow water equivalent at each point were then obtained by a regression equation relating measured values (from the snow survey conducted in mid-May, 1973) to elevation, convexity, and the cosine of aspect with respect to the prevailing west wind. The regression explained 70 % of the variance at a highly significant level. Snow was assumed to be absent wherever the slope exceeds 40°, based upon inspection of aerial photographs taken on January 24, 1973.

Meteorological data recorded in 1973 at two points in the basin (designated as D-4 and D-1 in INSTAAR records) at 3570 m (11700 ft) and at 3750 m (12284 ft) were used for input data to the model, except for wind speeds for which the only records were sporadic measurements starting June 25 on Niwot Ridge about 1 km east of the study area. In view of the incompleteness of the anemometer data, mean morning and afternoon values for the length of record were used throughout the period of snowmelt computation (May 17-August 24). This has undoubtedly led to considerable error in sensible and latent heat fluxes on certain days, but as these terms are generally much smaller than the radiation terms, it is hoped that the errors introduced are not too severe.

Certain changes were made in the computer program described by Williams (1974). The actual temperatures and humidities recorded were

used as input (at two hour intervals) rather than assuming sinusoidal diurnal variations between maxima and minima. Use of actinograph records from D-1 made possible the definition of atmospheric transmissivity, cloud transmittance, and cloud cover as those which would give the observed solar radiation, and furthermore cloud cover could be partitioned into unequal morning and afternoon amounts, an important consideration in this area where summer afternoons are usually cloudier than mornings. Precipitation, when it occurred, was not distributed evenly throughout the day but assumed to occur when relative humidity was maximum or whenever it exceeded 90 %. This should give better definition to the deposition of fresh snow. Finally, albedo was made to change not only with surface character (fresh snow, old snow, firn) but also to decrease in proportion to surface melting when old snow was exposed.

The results of this study are shown in Figures 1-3. In Figure 1, the computed amount of water available for runoff each day is compared with the measured discharge at Lake Albion inlet. The former is the sum over the basin of meltwater and rain which percolates through the snow (but since the snow is assumed isothermal in this case, it is simply the sum of snowmelt and rain). Clearly this cannot be expected to be the same as discharge from the basin, for no attempt has been made to account for travel times, groundwater storage, etc. However, the computed available water curve shows roughly the same trend as the hydrograph. Comparison of calculated ablation at individual grid points with ablation measured at nearby stakes from June 18 to August 20 shows that the model underestimated ablation during the first two of these nine weeks, but was about right thereafter.

In order to ascertain the effects of natural year-to-year variation in winter snowpack, two more experiments were run with the model. It was assumed that the 1973 snowpack was about normal (based upon records at the nearby "University Camp" snowcourse) and that the range of normal variation in winter snowpack is about ± 50 % in this region (T.N. Caine, pers. comm.). Thus, using the same May 17-August 24, 1973, meteorological data for purposes of comparison, the model was run with a 50 % increase

and with a 50 % decrease in initial snow water equivalent at each point. The lower curves in Figure 2 compare daily values of available water obtained from these two experiments (dashed lines) with those calculated for 1973 (solid line). In order to emphasize the variation of the effects trough the melt season, the ratios of available water from the two experiments to that computed for 1973 are plotted as the upper curves in Figure 2. An interesting result shows up in this plot. While the magnitudes of the effects become pronounced in both cases just after the peak runoff (the second week in July in this case), the available water is particularly enhanced during the first two weeks of August by the 50 % snowpack increase. In contrast, the diminishment of available water with a 50 % snowpack decrease merely oscillates around the 50 % level after July 9.

The set of figures collectively labeled Figure 3 show the snow water equivalent remaining at each grid point in the basin, according to the model, at one week intervals for the 50 % increased (upper map), 1973 (middle map), and 50 % decreased (lower map) snowpacks. The assymetry in effects of increased and decreased snowpacks is again evident in the extent of snowcover. While the snowcover extent with a 50 % decrease in winter snowpack begins to show an appreciable difference from 1973 by July 2, the difference in snowcover from 1973 with a 50 % snowpack increase is not very pronounced until the last week in July. Since ablation was underestimated from June 18 to July 2, the effects possibly would be evident somewhat earlier; however, it is reasonable to suppose that the asymmetry would remain.

References.

Sharpnack, D.A. and Akin, G., 1969. An algorithm for computing slope and aspect from elevations. Photogrammetric Engineering, 35(3), pp. 247-248.

Williams, L.D., 1974. Computer simulation of glacier mass balance throughout an ablation season. Proceedings Western Snow Conference, Anchorage, Alaska, April, 1974 (in press).

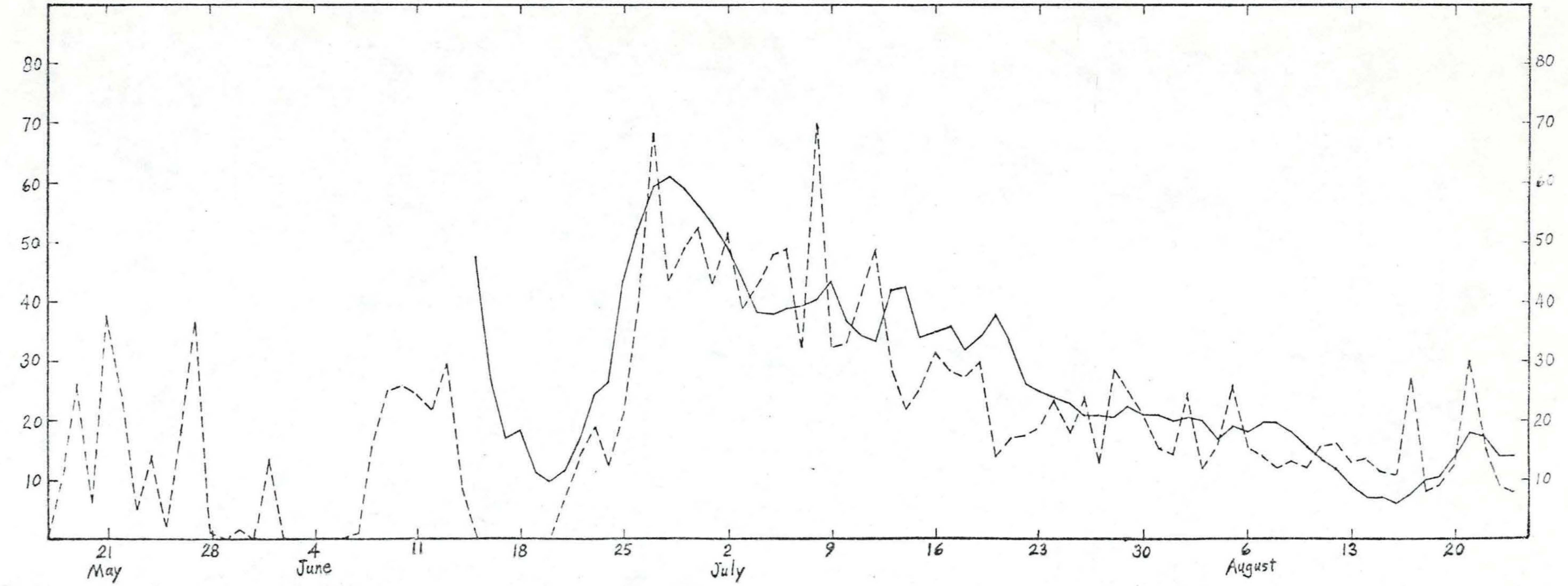


Fig. 1

FIGURE 1 Caption

Daily available water (total meltwater and rain over the basin computed by model from May 17-August 24, 1973 (dashed line) and daily discharge measured at Lake Albion inlet from June 15-August 24, 1973 (solid lines). Units are thousands of cubic meters.

FIGURE 1

FIGURE 2 Caption

Lower: Comparison of daily available water computed for 1973 (solid line) with that computed with a 50% increase in May 17 snowpack (upper dashed line) and with a 50% decrease in May 17 snowpack (lower dashed line). Units are thousands of cubic meters.

Upper: Ratios of computed available water with 50% snowpack increase (upper curve) and 50% snowpack decrease (lower curve) to that computed for 1973.

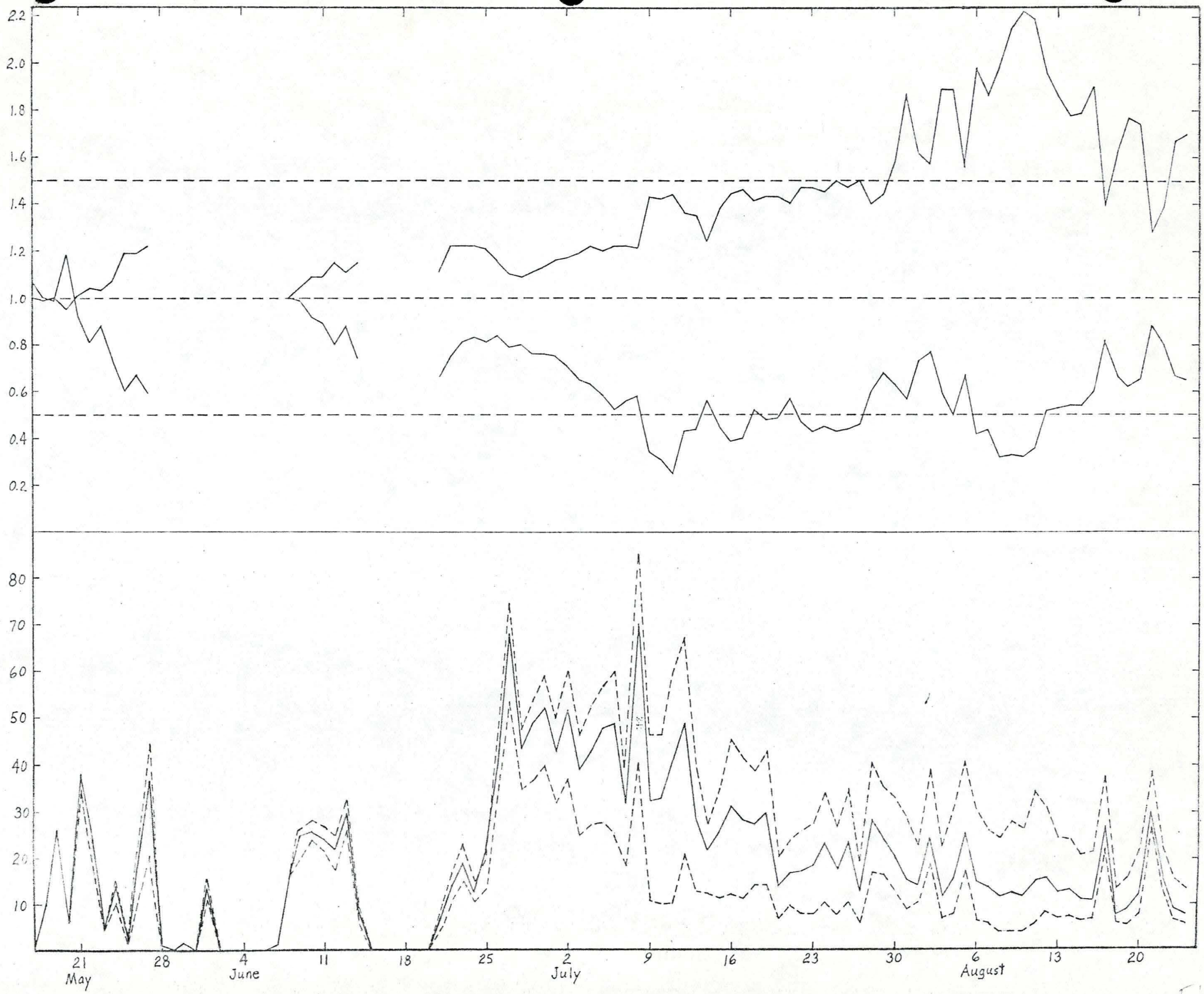


FIGURE 2

Fig. 2

FIGURE 3 Caption

Computed values of snow water equivalent (cm) remaining at grid points in basin of Green Lakes Valley above Lake Albion inlet, at weekly intervals, for May 17 snowpack 50% greater than 1973 (upper), for 1973 (middle), and for May 17 snowpack 50% less than 1973 (lower). Contour interval of topographic map 61 m (200 ft).

FIGURE 3
May 21, 1973

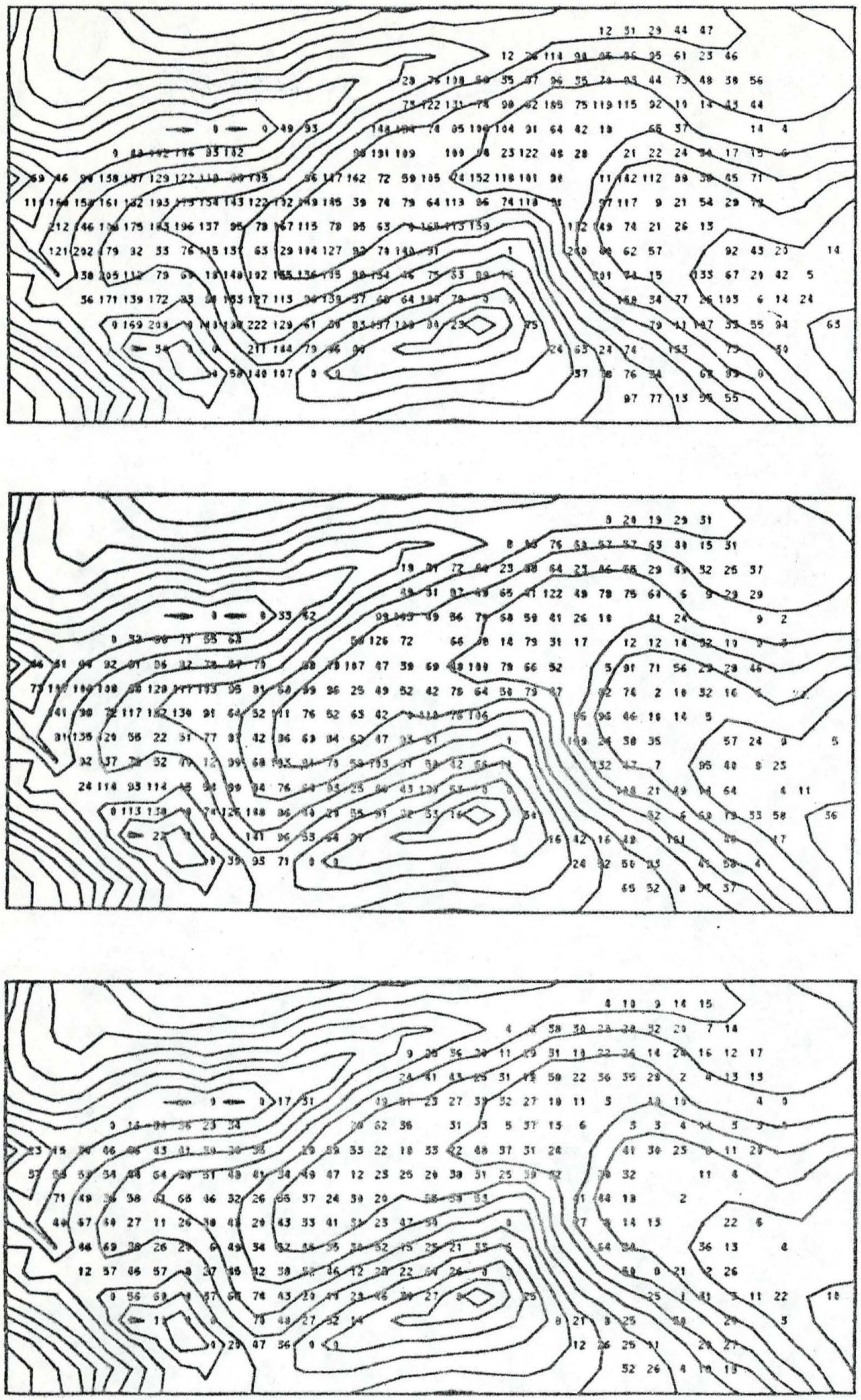


FIGURE 3
May 28, 1973

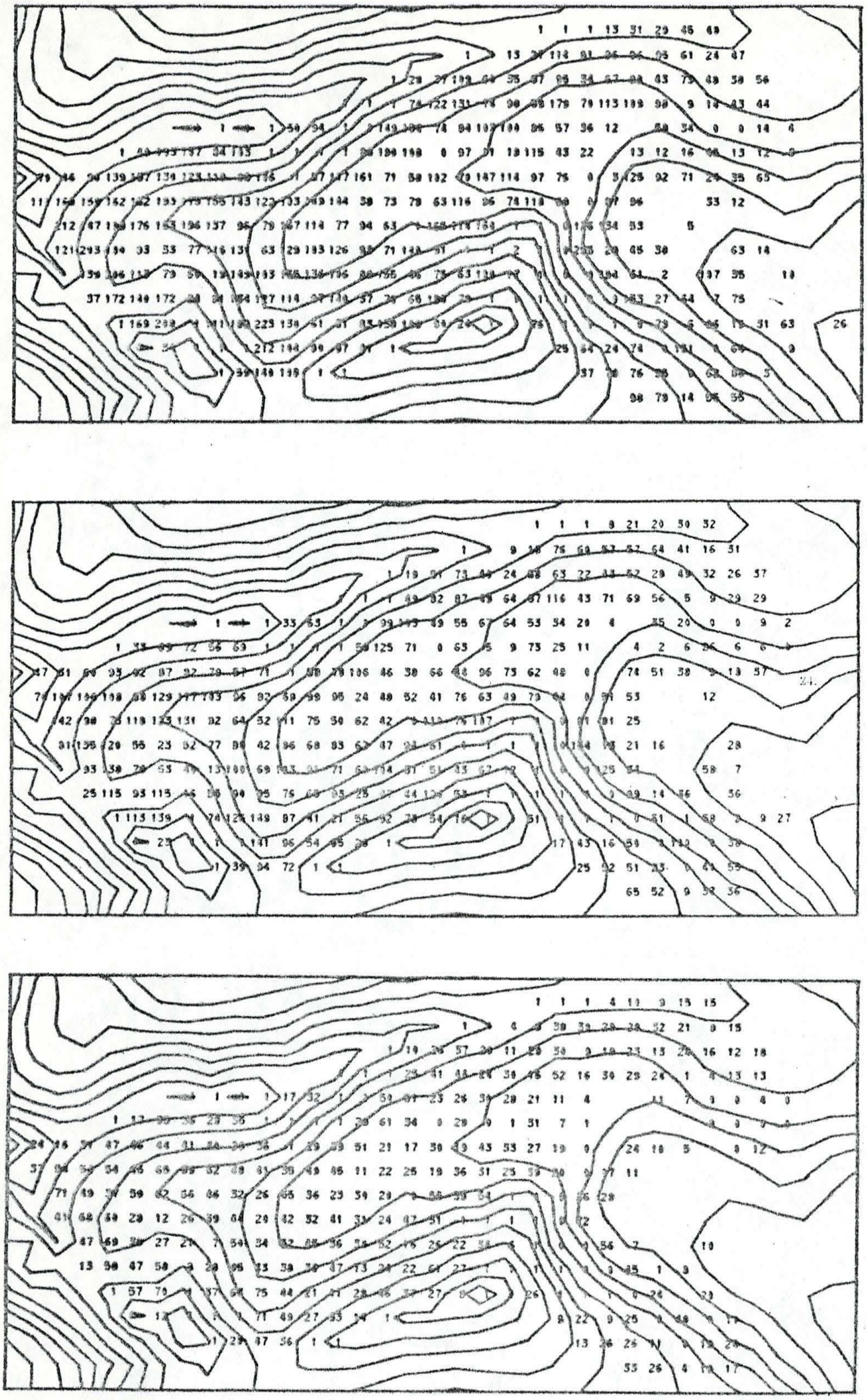
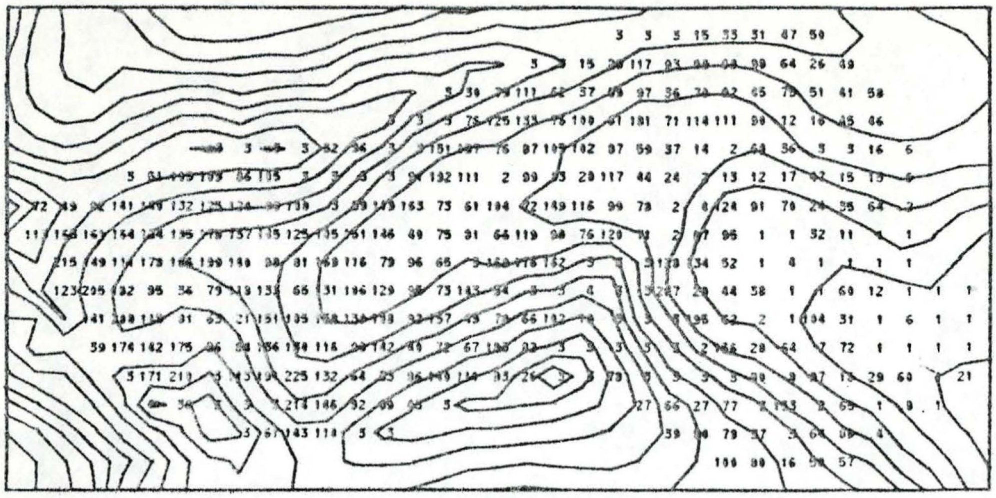
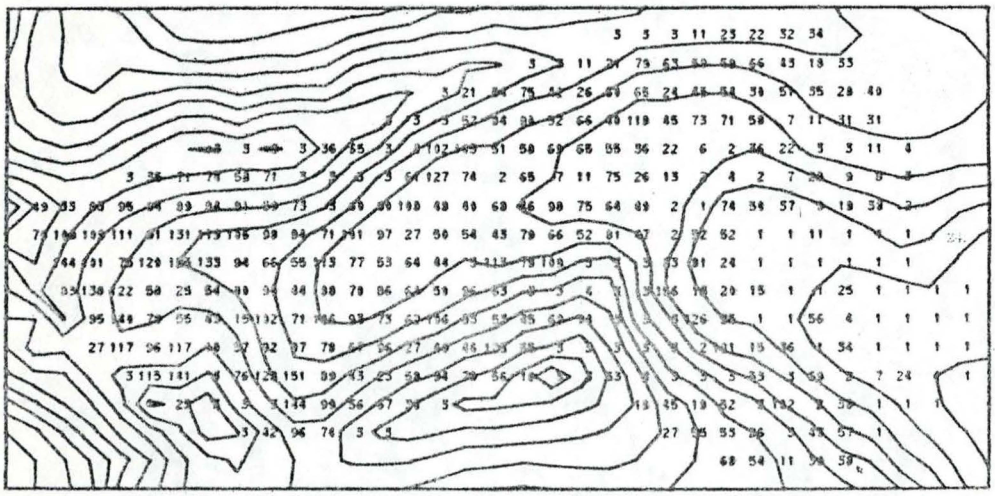


FIGURE 3
June 4, 1973





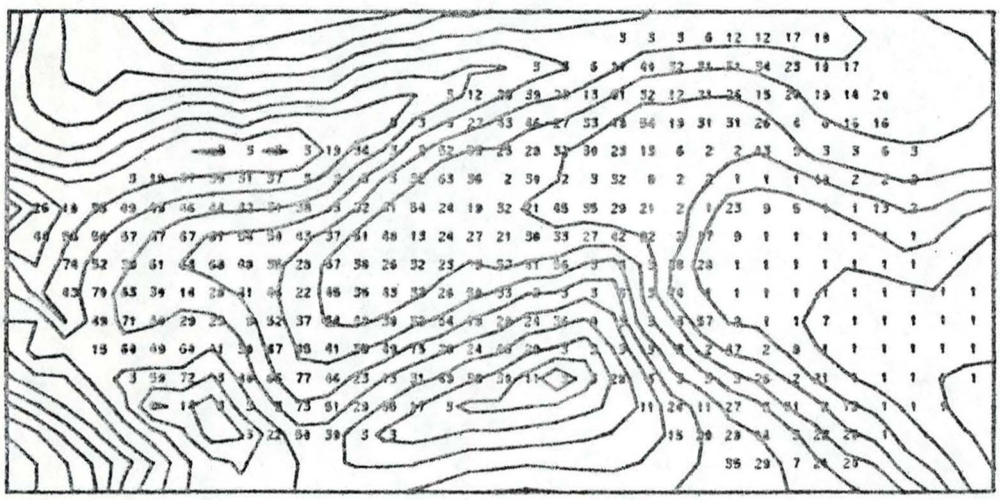


FIGURE 3
June 11, 1973

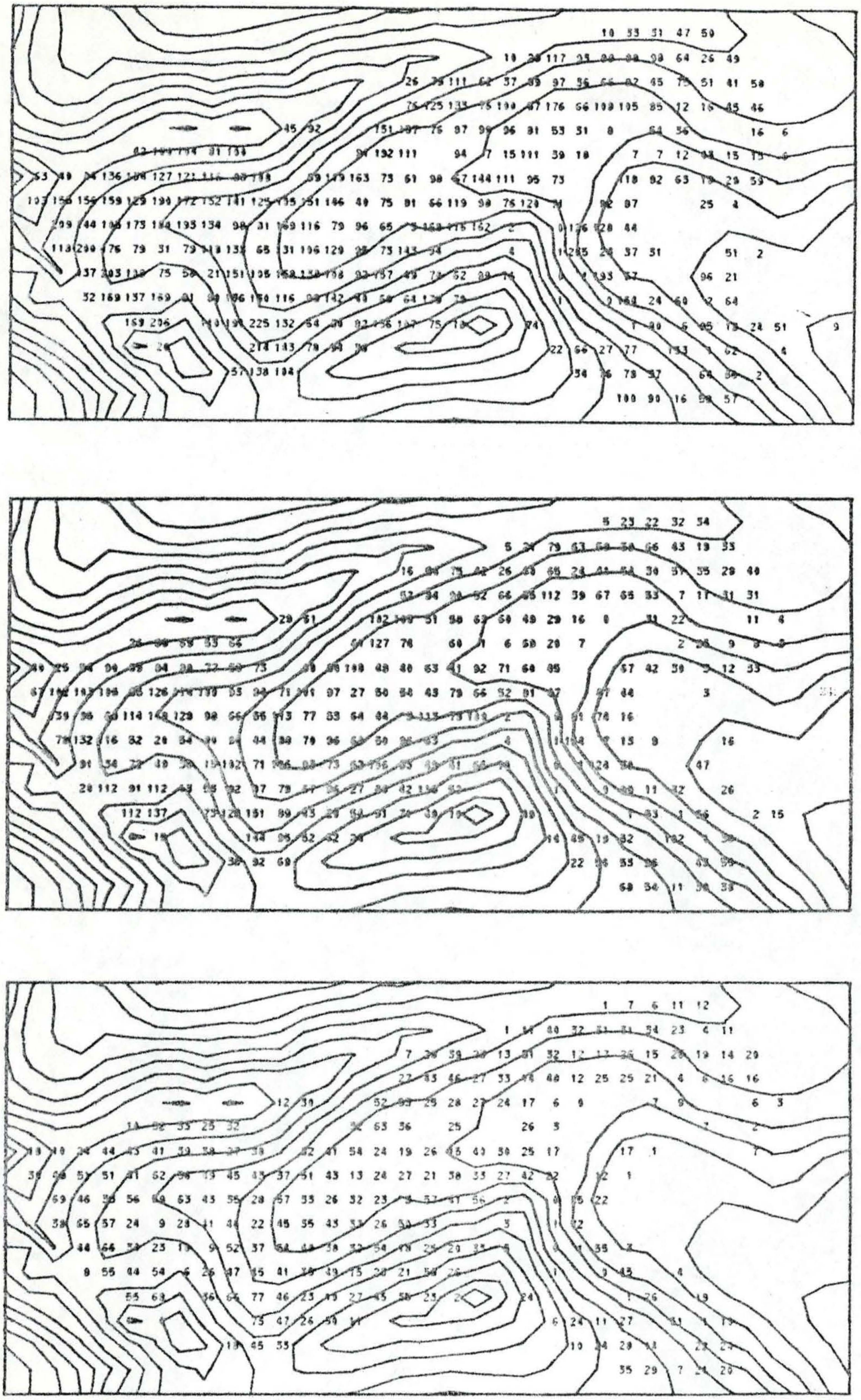
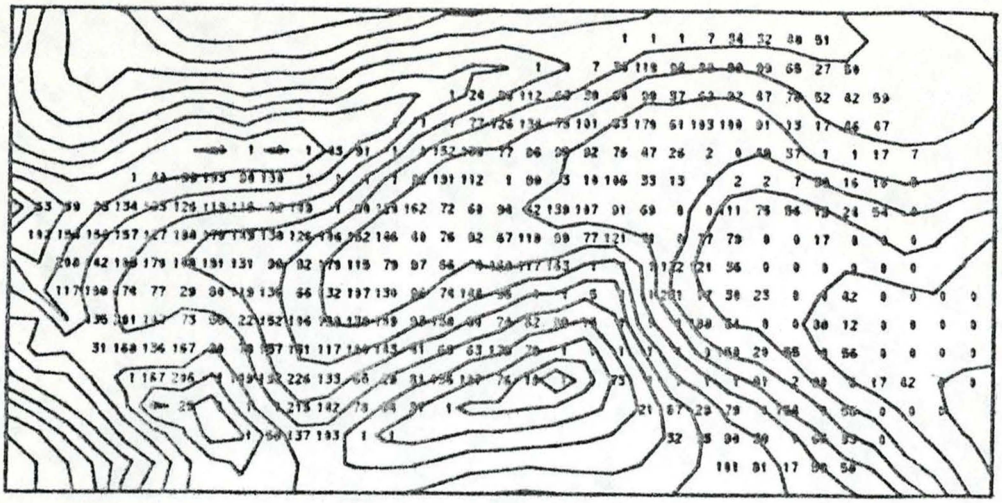
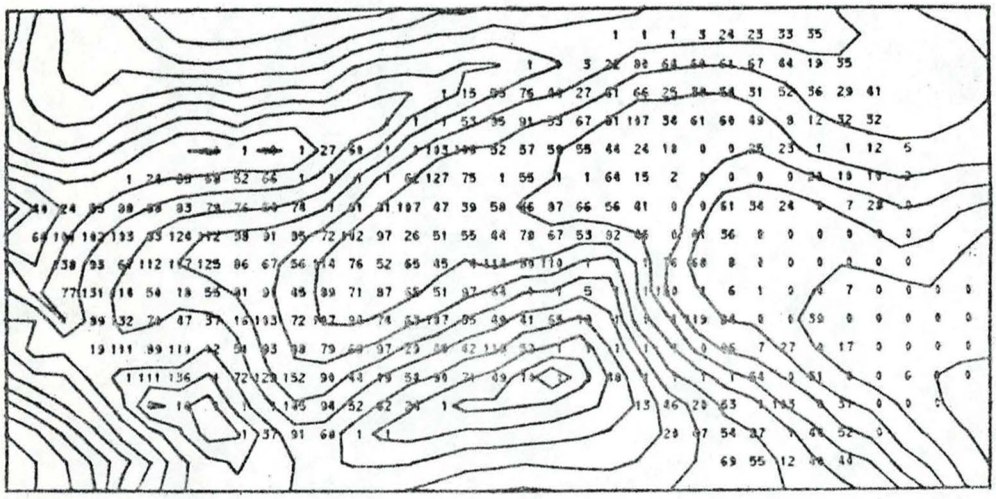
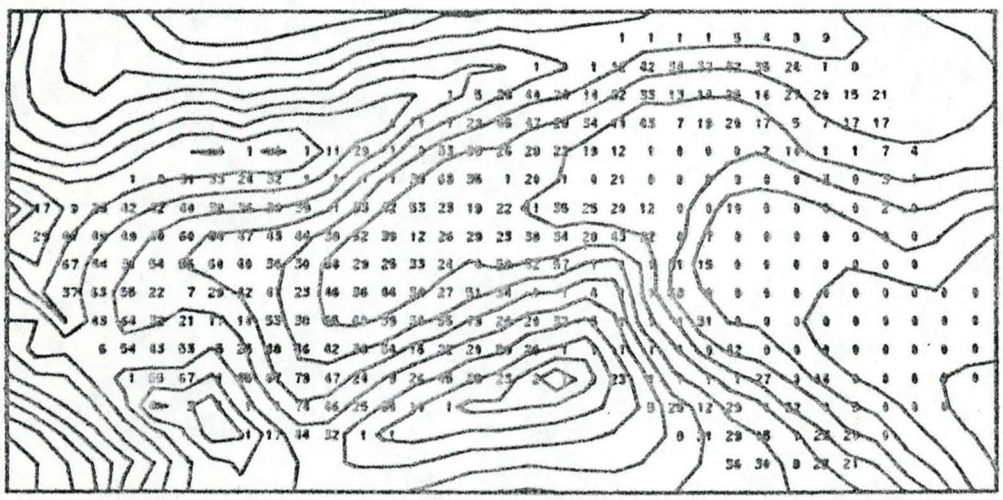
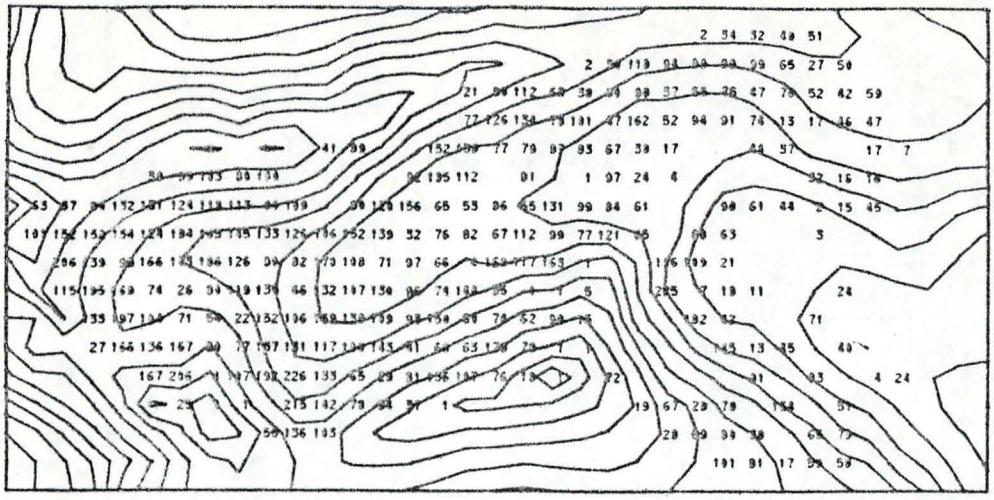


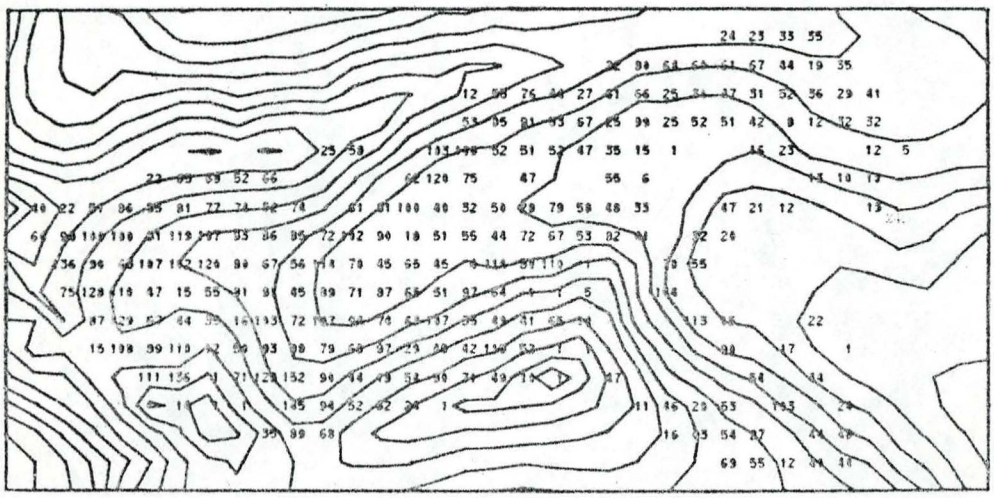
FIGURE 3
June 18, 1973











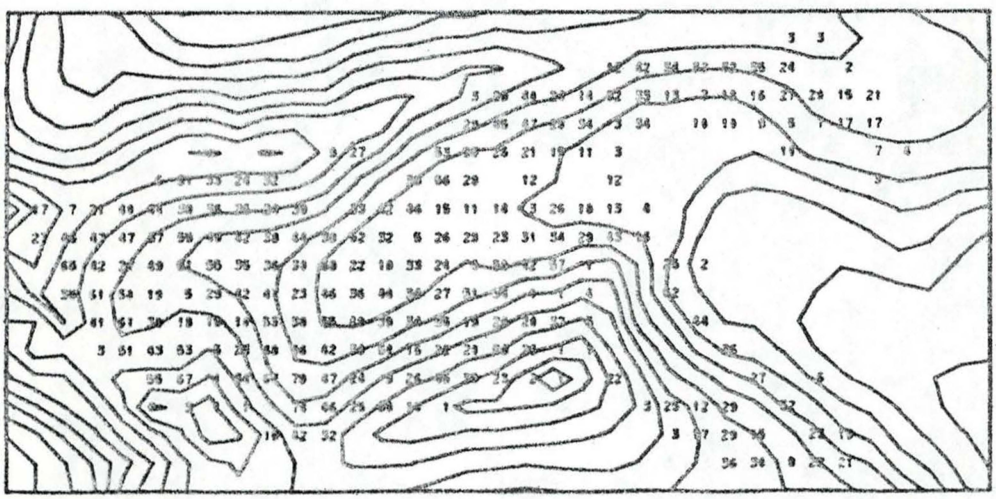


FIGURE 3
July 2, 1973

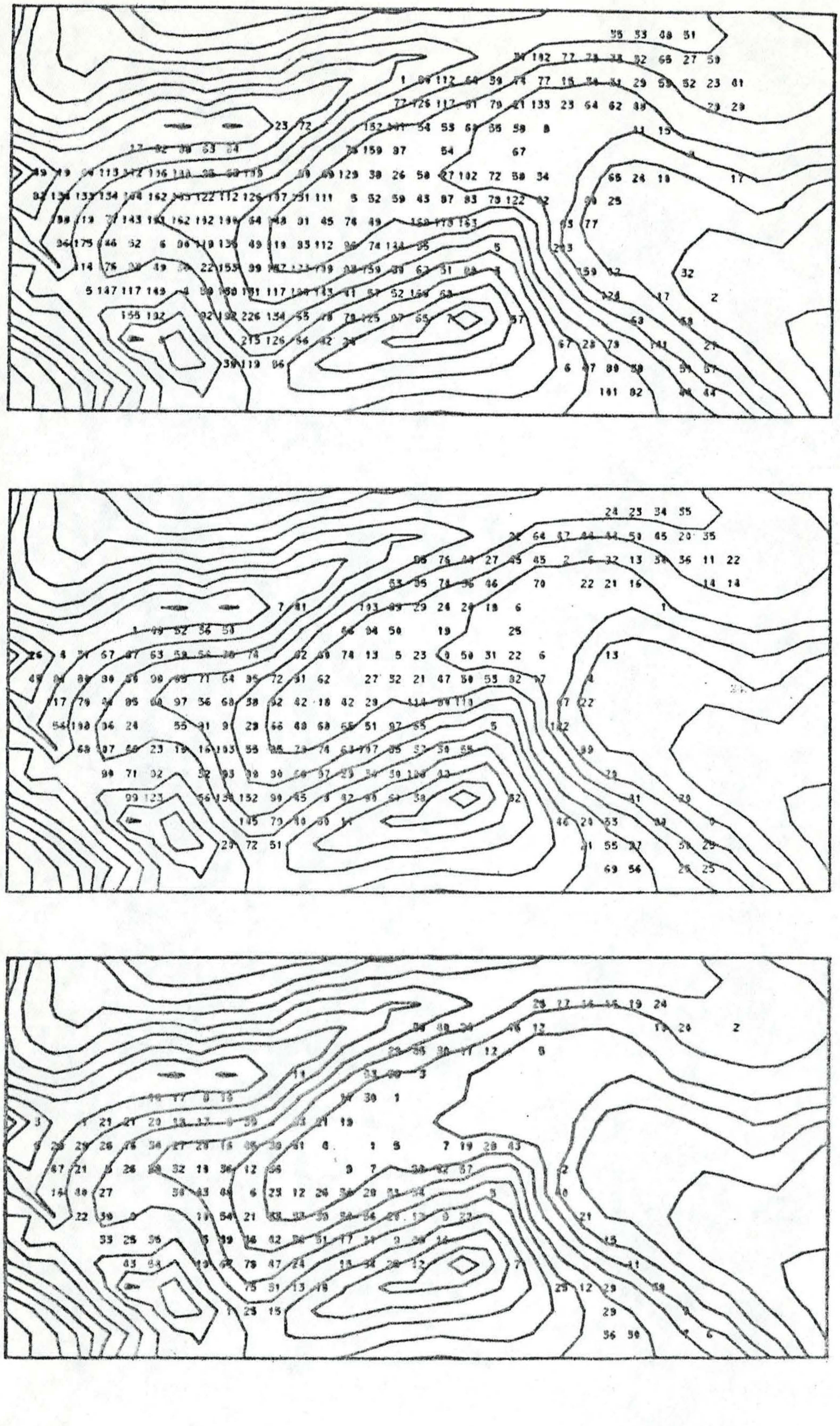


FIGURE 3
July 9, 1973

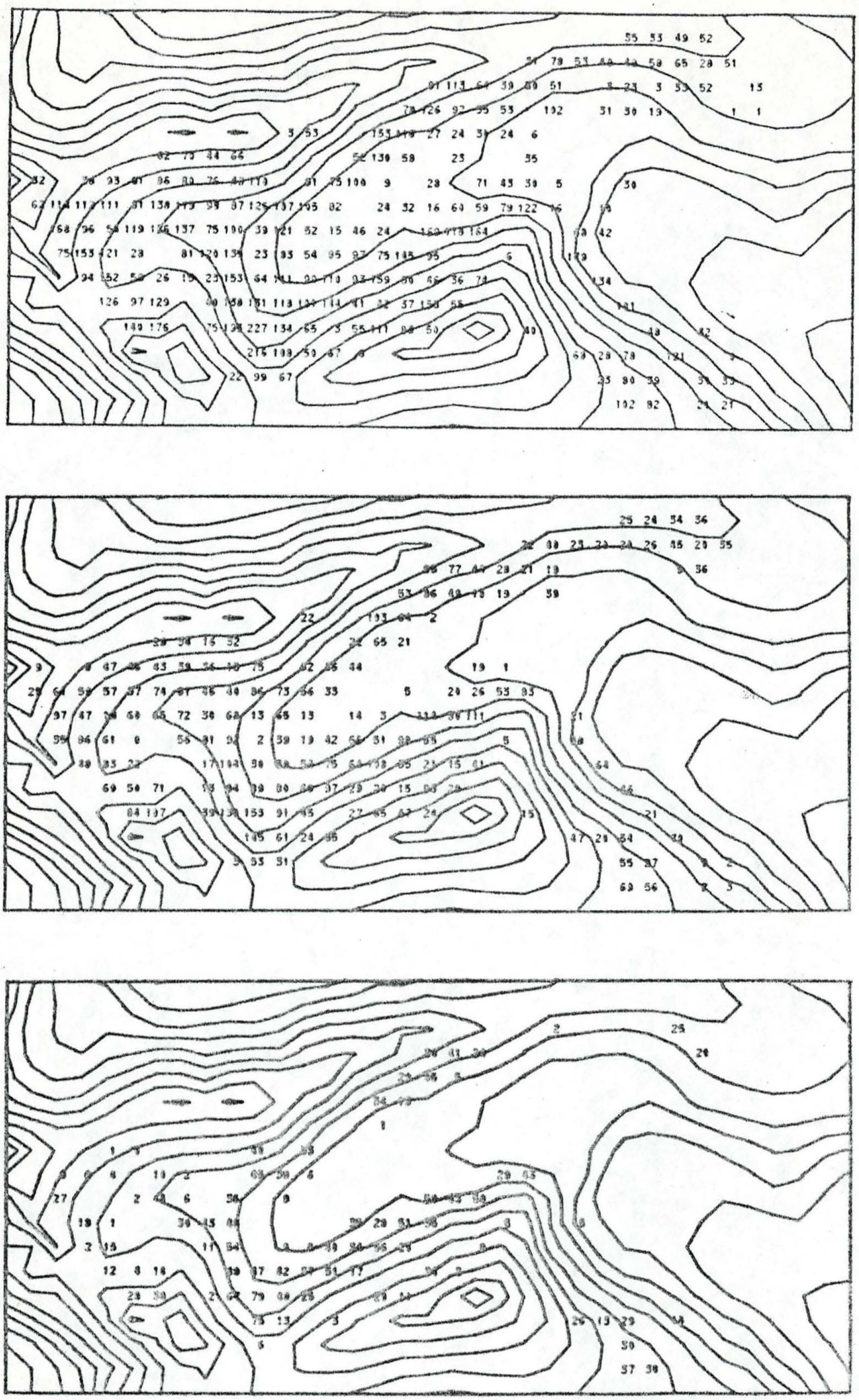


FIGURE 3
July 16, 1973

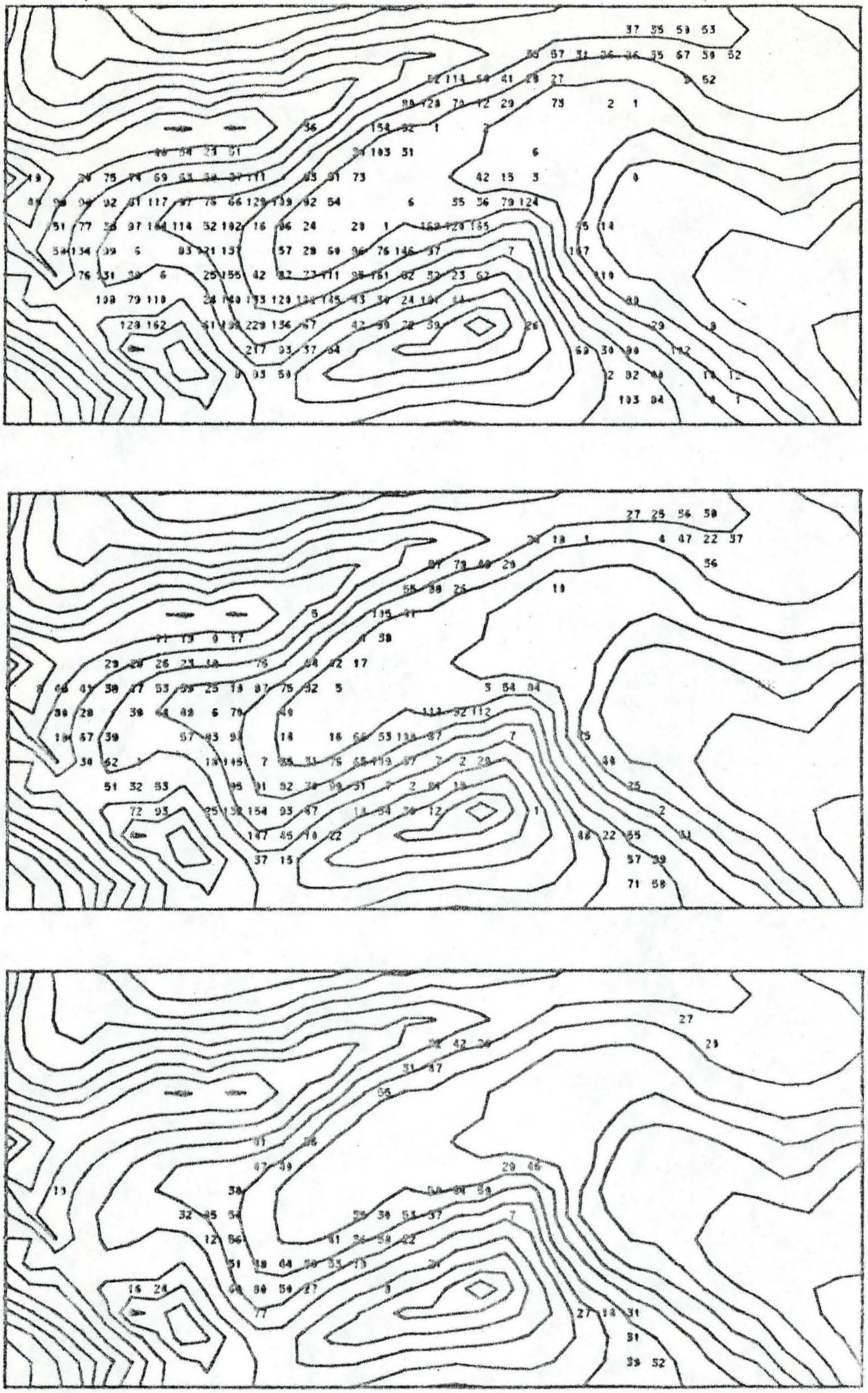
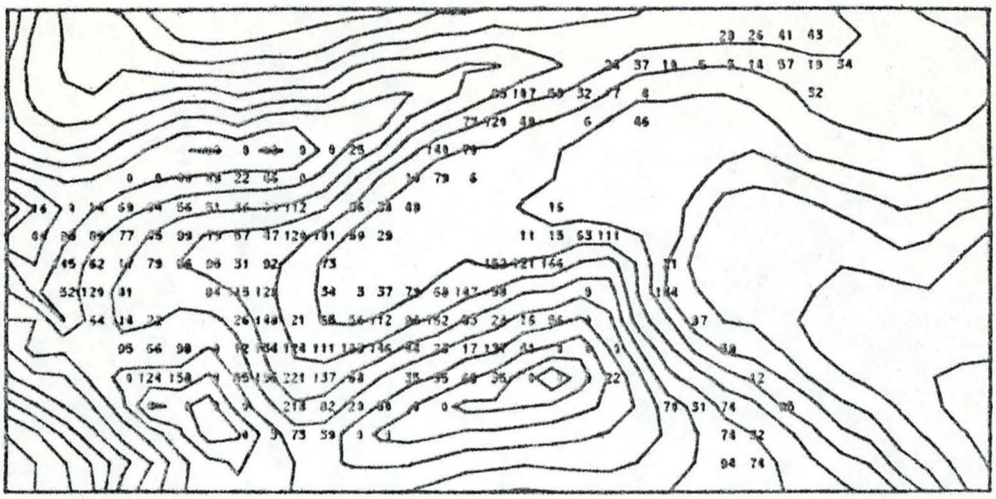
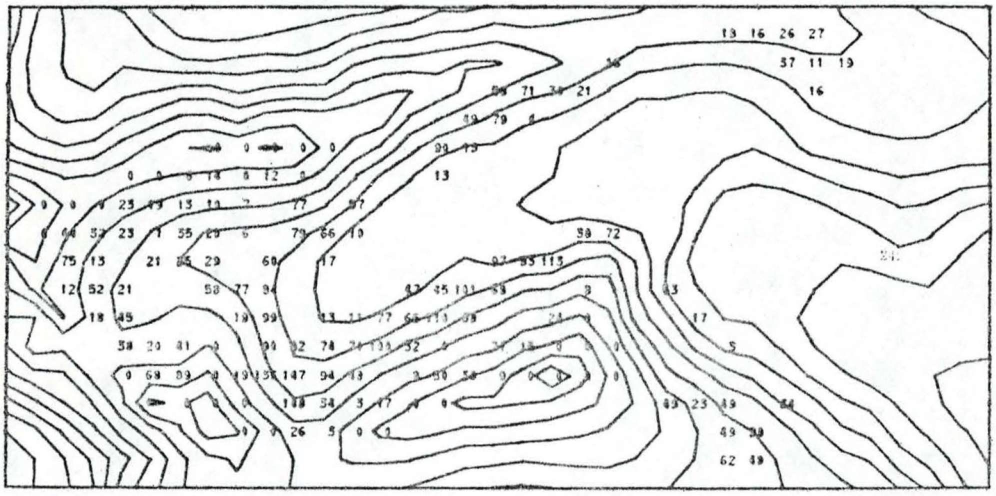


FIGURE 3
July 23, 1973





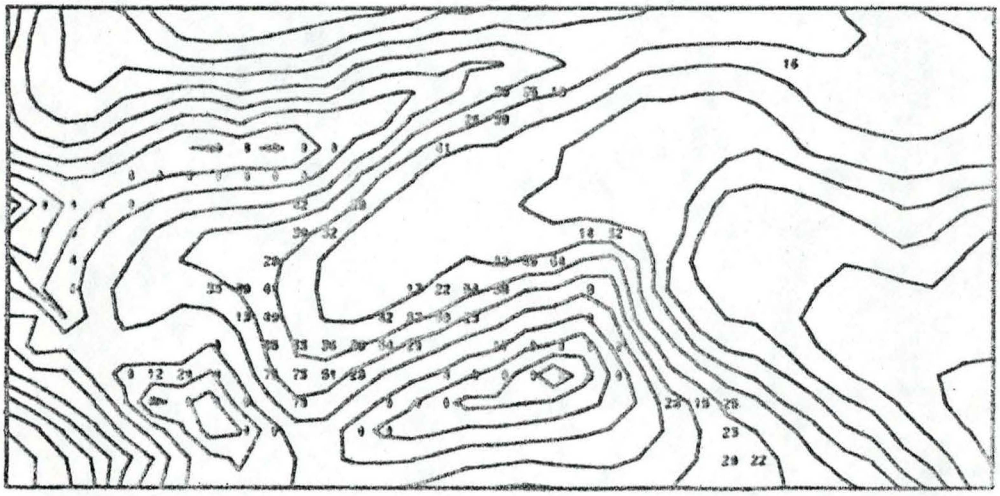


FIGURE 3
July 30, 1973

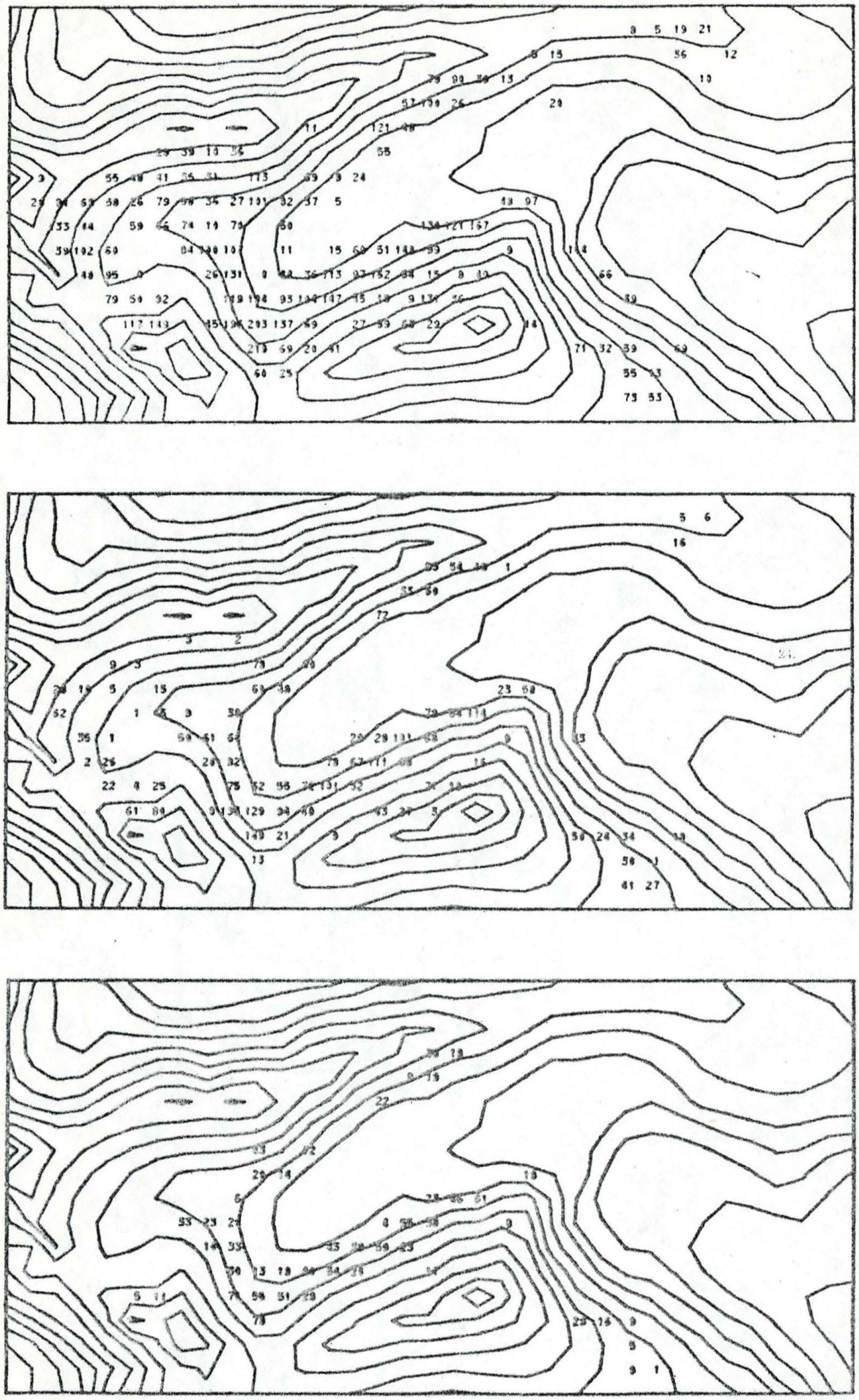
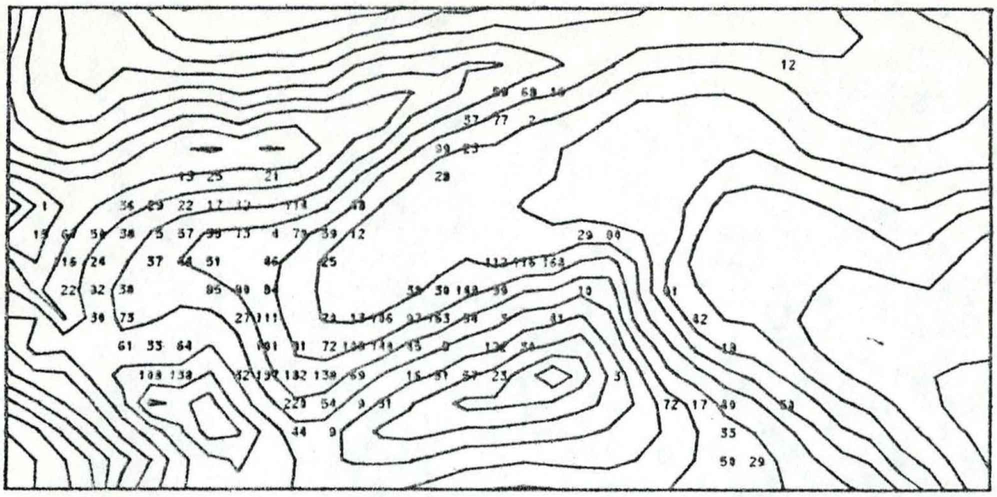
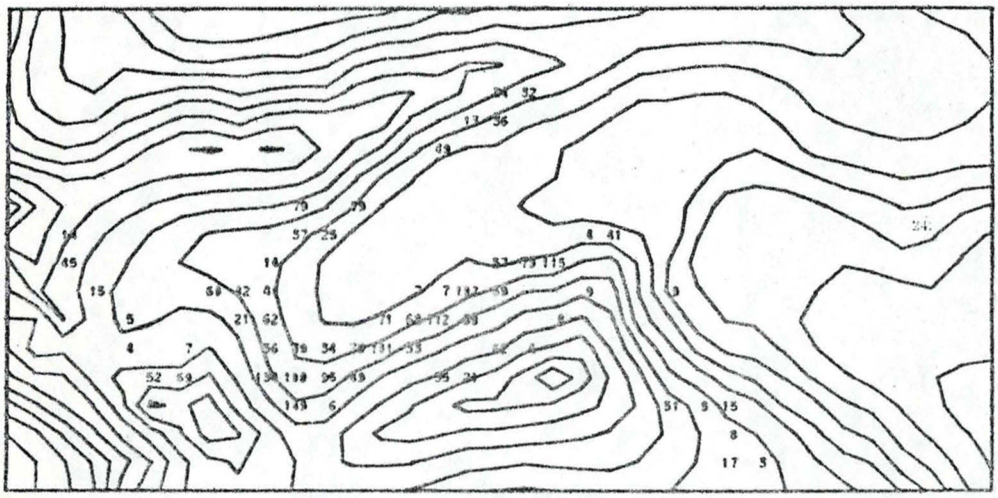


FIGURE 3
August 6, 1973





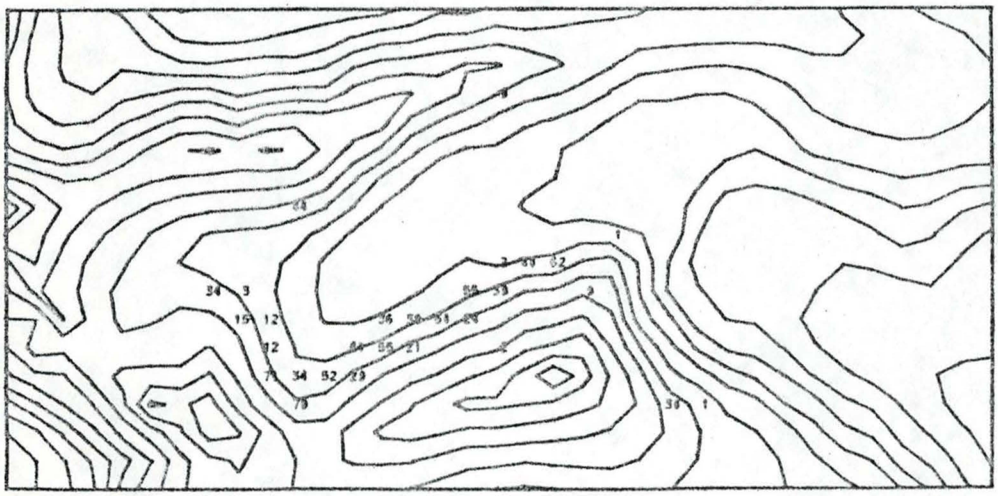


FIGURE 3
August 13, 1973

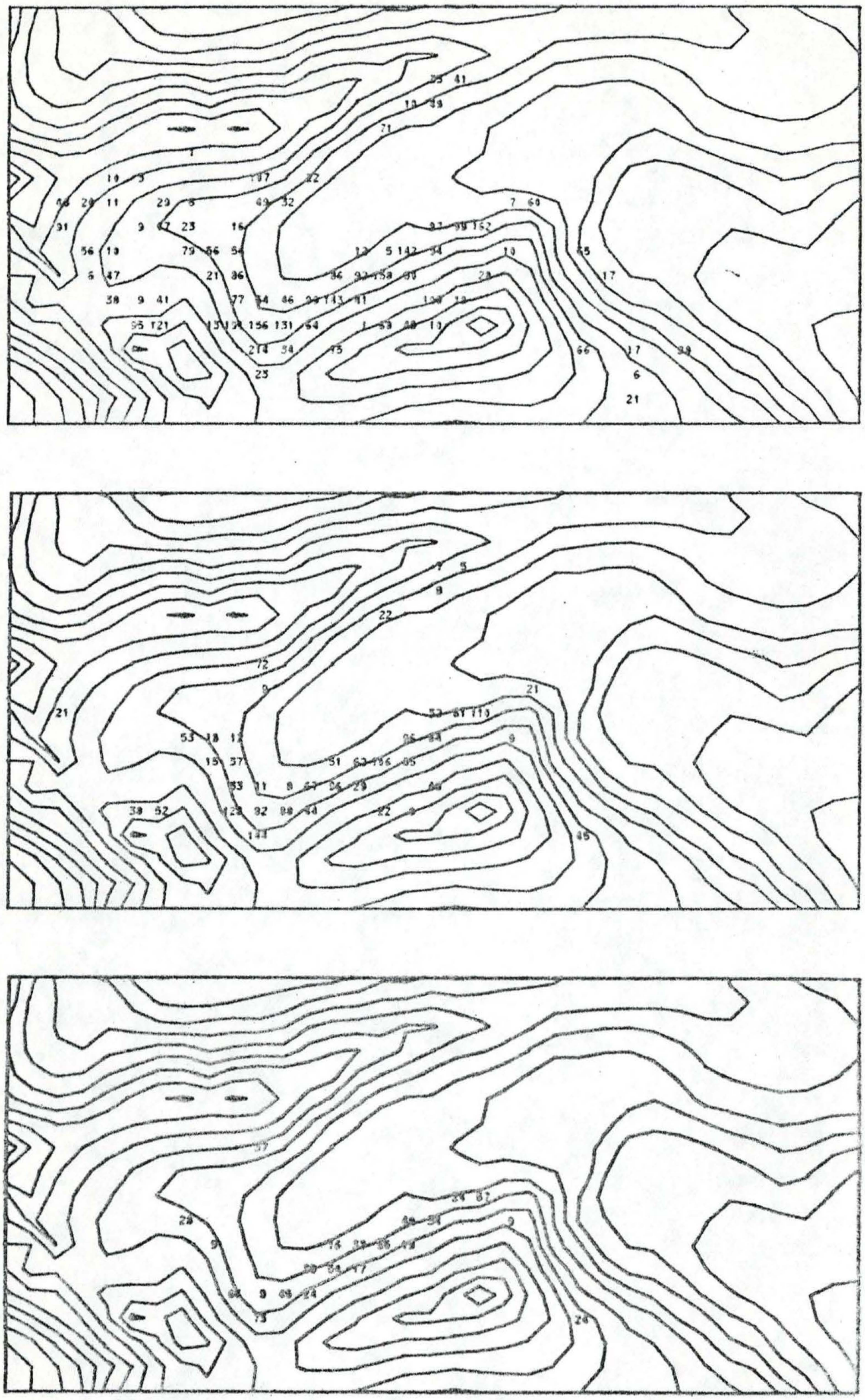


FIGURE 3
August 20, 1973